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**LEVEL**

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**LIGHT AIRCRAFT ENGINES, THE POTENTIAL AND  
PROBLEMS FOR USE OF AUTOMOTIVE FUELS  
PHASE 1 - LITERATURE SEARCH**

AD A094154

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FINAL REPORT

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## Technical Report Documentation Page

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16. Abstract <p>A comprehensive data research and analysis for evaluating the use of automotive fuels as a substitute for aviation grade fuel by piston-type general aviation aircraft engines is presented. Historically known problems and potential problems with fuels were reviewed for possible impact relative to application to an aircraft operational environment.</p> <p>This report reviews areas such as: fuel specification requirements, combustion knock, preignition, vapor lock, spark plug fouling, additives for fuel and oil, and storage stability.</p>					
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# METRIC CONVERSION FACTORS

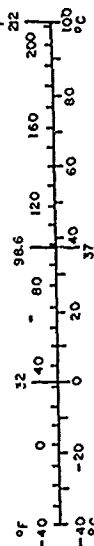
## Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	6.5	square centimeters	cm <sup>2</sup>
ft <sup>2</sup>	square feet	0.09	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yards	0.8	square meters	m <sup>2</sup>
mi <sup>2</sup>	square miles	2.6	square kilometers	km <sup>2</sup>
	acres	0.4	hectares	ha
<b>MASS (weight)</b>				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
<b>VOLUME</b>				
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft <sup>3</sup>	cubic feet	0.03	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.75	cubic meters	m <sup>3</sup>
<b>TEMPERATURE (exact)</b>				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

\*1 in = 2.54 (exactly). For other exact conversions, see more detailed tables, see NBS Mon. Publ. 1. Units of Length and Masses, Price \$2.25; 50 Calling No. C13.10-286.

## Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
<b>AREA</b>				
cm <sup>2</sup>	square centimeters	0.16	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	1.2	square yards	yd <sup>2</sup>
km <sup>2</sup>	square kilometers	0.4	square miles	mi <sup>2</sup>
ha	hectares (10,000 m <sup>2</sup> )	2.5	acres	
<b>MASS (weight)</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
<b>VOLUME</b>				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
m <sup>3</sup>	cubic meters	0.26	gallons	gal
m <sup>3</sup>	cubic meters	35	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.3	cubic yards	yd <sup>3</sup>
<b>TEMPERATURE (exact)</b>				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



# TABLE OF CONTENTS

	Page
INTRODUCTION	1
OVERALL CONCLUSIONS AND OBSERVATIONS	1
DETAILED CONCLUSIONS	2
EXISTENCE OF GASOLINE SPECIFICATIONS IN THE UNITED STATES	4
PERFORMANCE REQUIREMENT SPECIFICATIONS	9
Octane Rating	9
Distillation	11
Volatility	12
Composition	15
Additives	16
Stability	17
Deposit Characteristics	17
EXTENT OF SOME RELEVANT MANDATORY REQUIREMENTS	18
FAA Requirements	18
State Requirements	19
GASOLINE VARIABILITY IN THE UNITED STATES	19
WHICH AVGAS CAN BE REPLACED BY AUTOGAS AND WHY	27
DETAILED DISCUSSION OF POTENTIAL PROBLEM AREAS	27
Combustion Problems	27
Knock	27
Preignition and Deposit Ignition	28
Volatility Related Effects	31
Vapor Lock	31
Icing	39
Cold Start and Warm Up	43
Maldistribution	43
Spark Plug Fouling	44
Hot Restart	45
Fuel Safety	47
Engine Durability	48
Exhaust Valve Life	48

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Unannounced	<input type="checkbox"/>
Justification	
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Distribution/	
Availability Codes	
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## TABLE OF CONTENTS (Concluded)

	Page
Valve Seat Recession	48
Engine Wear	49
Compatibility with Materials and Corrosion	50
Non-Metallic Materials	50
Metallic Materials	55
Gasoline Storage Stability	58
 ADDITIVES FOR PETROLEUM PRODUCTS	 63
Additives for Lubricants	63
Antioxidants	67
Corrosion Inhibitors	67
Anti-Wear Agents	67
Detergents	67
Dispersants	67
Viscosity Index Improvers	68
Rust Inhibitors	68
Pour Point Depressants	68
Anti-Foam Agents	69
Ashless Additive	69
Additive Concentration	69
Additives for Gasoline	70
Antiknock Compounds	71
Deposit Modifiers	75
Surface Ignition	75
Antioxidants	76
Metal Deactivators	77
Antirust Agents	77
Antiicing Agents	78
Detergents	79
Upper Cylinder Lubricants	79
Dyes	79
Oxygenated Fuel Blending Agents	80
 SUMMARY	 82
 REFERENCES	 85
 APPENDIX	
Tables A-1 through A-7	
Alphabetical Bibliography	

# LIST OF ILLUSTRATIONS

Figure		Page
1	Relationship Between the ASTM Distillation Curve and Engine Performance	13
2	Maximum ASTM Distillation Requirements for Avgas and Autogas	14
3	Comparison of Actual 80/87 Avgas and Regular Autogas Distillation Data from Surveys with the Maximum Avgas Distillation Requirements of ASTM	20
4	Comparison of Average Distillation Data from Surveys of Regular Autogas for Two Different Districts of the U.S. During the Winter '78-'79 with the Maximum Avgas Distillation Requirements of ASTM	21
5	Comparison of Actual Avgas and Autogas Motor Octane Rating Data from Surveys	22
6	Comparison of Actual Avgas and Autogas Reid Vapor Pressure Data from Surveys	23
7	Comparison of Actual Avgas and Autogas Lead Content Data from Surveys	24
8	Comparison of Actual Avgas and Autogas Sulfur Content Data from Surveys	25
9	Temperature-V/L Relation for Some Unleaded Autogas Samples at Sea Level Pressure	32
10	Temperature-V/L Relation for Some Regular Autogas Samples at Sea Level Pressure	33
11	Temperature-V/L Relation for Some Premium Autogas Samples at Sea Level Pressure	34
12	Temperature-V/L Relation for Some Aviation Grade 80/87 Samples at Sea Level Pressure	35
13	Effect of Altitude/Pressure on the Temperature V/L Relation of One Sample of 80/87 Grade Avgas	36
14	Reduction of Atmospheric Temperature with Altitude	38

# LIST OF ILLUSTRATIONS (Concluded)

Figure		Page
15	Canadian Department of Transport Icing Probability Curves	440
16	Effect of Fuel Volatility on Throttle-Plate Temperature	41
17	Relative Plug Fouling Time Versus Lead Content for a Laboratory, Four Cylinder, Air-Cooled Aircraft Engine	46
18	The Effect of Toluene/Isooctane Blends at 21°C on the Volume Increase of Some Fuel System Rubbers	56
19	Effect of Temperature on Stability of Typical Aviation Gasoline	61
20	Type of Failure in 110°F Storage of Commercial Autogas Samples (TEL Content 2.6 to 3.2 g Pt/gal.)	62



# LIST OF TABLES

Table		Page
1	Avgas and Autogas Specifications	5
2	States Which Define Autogas Properties	7
3	States Which Define Avgas Properties	8
4	Solubility Parameters	53
5	Examples of Additives Used in Autogas	64
6	Examples of Additives Used in Automotive Lubricating Oils	65
7	Examples of Additives Used in Avgas	66
8	ASTM Tests for Motor Oils	71
9	Problem Severity Comparison	83
A-1	Regular Autogas Data, Summer 1979	
A-2	Premium Autogas Data, Summer 1979	
A-3	Unleaded Autogas Data, Summer 1979	
A-4	Regular Autogas Data, Winter 1978-79	
A-5	Premium Autogas Data, Winter 1978-79	
A-6	Unleaded Autogas Data, Winter 1978-79	
A-7	80/87 Avgas Data from 1969	

## INTRODUCTION

Over the years many pilots have reported on an informal basis that they have successfully used automotive gasoline (autogas) in their light aircraft. On the other hand, use of autogas is suspected to have caused engine malfunctions, some of which may have resulted in crashes (1). This study is an attempt to evaluate this dichotomy of views in terms of characteristics of autogas and aviation gasoline and how the differences might be expected to affect safety, engine performance, and durability.

Several key fundamental areas have been explored. These are:

- Antiknock properties
- Preignition and deposit ignition
- Vapor lock
- Icing
- Cold start
- Hot restart
- Fuel safety
- Valve sticking and wear
- Materials incompatibility and corrosion
- Maldistribution
- Spark plug operation
- Fuel storage stability

Each of the above areas has been evaluated based on the published literature which is cited in the References. An Alphabetical Bibliography has been included at the end of this report. No experimental work has been performed in connection with this effort.

## OVERALL CONCLUSIONS AND OBSERVATIONS

Below are presented the overall conclusions of this study. Detailed conclusions follow:

1. Based upon existing information the use of autogas in light aircraft is in general expected to create safety problems. It is obvious that some aircraft and some batches of autogas will perform satisfactorily depending on ambient temperature, altitude obtained, mode of operation, and fuel system design. Under other circumstances serious problems can arise quickly and there is considerable potential for longer-range problems of materials and engine durability which may or may not create a dangerous problem.

2. Many of the technical studies of aircraft fuels have been conducted during or prior to World War II and therefore are relatively old. Few recent studies exist. There is considerable lack of data on just how fuel property variations affect the performance and durability of aircraft engines. This situation does not support conclusions in many areas.

3. Based on available information it cannot be determined with certainty that future engine/aircraft designs can be developed that will be entirely tolerant of the widely varying properties of autogas, properties whose variations are steadily growing as refiners attempt to maximize gasoline yield in response to higher prices. Research needs to be done to further delineate key problem areas and potential solutions. Standard tests need to be developed by which new fuel system designs can be evaluated. Such tests may employ a set of standard fuels whose properties reflect those of autogas which has wide variations season to season and from one part of the country to another. If aircraft can be developed which are compatible with autogas, they are likely to be more complex and expensive than current models.

#### DETAILED CONCLUSIONS

1. There is only one grade of avgas that can be replaced by autogas because of antiknock quality, that is grade 80/87. Regular, premium, and lead-free automotive gasolines all appear to have sufficient Motor octane quality. The lack of a general correlation between the Aviation Supercharge and Automotive Research octane numbers precludes any decision with respect to this rating. Although some evidence exist which suggests that the autogas Rich rating is adequate for grade 80/87.

2. Use of autogas with its higher aromatic content and higher volume of low boiling point constituents is expected to increase combustion chamber deposits which in turn can aggravate knock-induced preignition. Moreover it is known that some aromatic compounds tend to preignite easily. Some engines are likely to have greater preignition problems depending on cylinder cooling. The heating value specification for avgas effectively limits aromatic content to about 25%.

3. Vapor lock is known to be a problem occasionally even with avgas which has a maximum Reid vapor pressure of 7 lbf/in.<sup>2</sup> With autogas, the maximum Reid pressure can approach 16 lbf/in.<sup>2</sup>, and this increases the likelihood of vapor lock considerably. This problem is greater for a low wing aircraft and might be ameliorated by a suitable intank fuel pump. Vapor lock is probably the most important safety-related problem needing solution before autogas can replace avgas.

4. Carburetor icing appears to pose a somewhat greater problem with autogas than with avgas. Some improvements in icing can be realized by the addition of antiicing compounds to those fuels not already containing them.

5. Although specific data are not available for aircraft, a consideration of the automotive literature indicates that the higher front end volatility of autogas can be expected to ease starting and warm up in cold weather operation.
6. Hot restart on the ground may be expected to be more difficult with autogas because of increased deposit ignition and vapor lock. Significant differences are expected at altitude also when vapor lock is present.
7. A search of the literature reveals that gasolines with high boiling point constituents (autogas) create greater problems of valve sticking and valve guide deposits. These arise from contamination of the lubricant and/or deposits of unburned fuel components on the valve stems and guides themselves. More sludge and varnish are expected in the crankcase with autogas. This results from high blowby rates in aircraft engines and relatively low detergency in the oil.
8. The greater aromatic and olefinic content of automotive gasolines is known to adversely affect the performance and durability of polymeric and rubber fuel system materials. Problems arise when critical dimensions are exceeded and parts stick, or when physical properties are deteriorated.
9. The greater sulfur level and higher levels of halogen scavengers in autogas can be expected to increase acid corrosion of the engine, a long-term durability problem.
10. There is no data to indicate the severity of valve seat recession problems in aircraft engines when lead-free autogas is used.
11. Maldistribution may be expected to be worse with autogas due to its greater boiling range. This can lead to engine roughness, knock and removal of lubricating oil from cylinder surfaces under low temperature operation. There is no indication of a safety problem from this source.
12. Spark plug fouling is expected to be increased with leaded automotive fuels because of their greater volume of high boiling point constituents and higher lead levels. With lead-free gasoline spark plug fouling will be reduced compared to some aviation gasoline due to the absence of lead compounds.
13. For equal storage time and temperature, storage stability is worse with autogas. This can contribute to increased gum with subsequent intake valve sticking and carburetor orifice plugging. Avgas is provided with a relatively high dosage of anti-oxidant to delay gum formation. On the other hand, use of fresh autogas will pose no gum problems and to the extent that fuel storage times are reduced because of a high turnover of autogas, perhaps gum problems would be reduced in practice.
14. Fuel safety in regard to toxicity and explosion hazard is about the same for all these gasolines.

## EXISTENCE OF GASOLINE SPECIFICATIONS IN THE UNITED STATES

Gasoline specifications define various characteristics of gasolines necessary for proper engine performance. For example, the octane rating, Reid vapor pressure and sulfur content are commonly specified properties. These specifications constitute a description of the gasoline. A list of such specifications for autogas and for avgas appear in Table 1.

The specifications in Table 1 are the 1979 voluntary standards of the American Society for Testing and Materials (ASTM) for autogas and avgas (2). Also, the United States federal government maintains military gasoline specifications.

Table 2 summarizes the extent to which different states apply the ASTM standards for autogas. From Table 2 it is seen that 36 states have agencies which regulate autogas quality for their state. These state agencies vary from the Department of Agriculture and Industries in the state of Alabama, to the Department of Labor and Employment, Division of Labor in the state of Colorado, to the Department of Administration, Weights and Measures Division in the State of Arizona.

According to "Key Reprints" from the Avco Lycoming Flyer (3), only six states require that ASTM or Federal Government specifications are to be met for autogas marketing in those states. Of the other states requiring some specifications, different states regulate various properties of the gasoline. Some states have no regulations, others may regulate only one or two properties of autogas. Inspection of Table 2 reveals this lack of continuity of autogas specifications throughout the U.S. These state laws regarding autogas are mostly in the form of Inspection Laws, although some are from state air laws. Also, nine states have a definition for aviation gasoline. These are also found under state inspection laws or air laws (4), and are noted in Table 3.

Other agencies exist which more indirectly regulate gasoline. The Environmental Protection Agency, for example, regulates additives to automotive gasolines and requires vehicle labels "unleaded gasoline only" (5). The Federal Aviation Administration specifies which fuel may be used in each aircraft (according to the manufacturer's specification) (5). In addition to these agencies, the Federal Trade Commission specifies how fuel dispensers for automotive gasoline display the fuel's octane number (5).

The variation of regulations (or lack of regulations) from state to state as noted above appears to allow a potential for variation of gasoline properties. But, the autogas business today is highly competitive, and therefore one goal of the gasoline refiner is customer satisfaction. This requirement of customer satisfaction greatly controls what the gasoline's performance will be. Since today's automotive engine is developed on current gasoline, only typical gasolines will operate well in these vehicles, which establishes constraints on the range of autogas properties in order to achieve this customer satisfaction. Gasolines therefore are known according to

TABLE 1. AVGAS AND AUTOGAS SPECIFICATIONS (ASTM TESTS D 910 AND D 439, REF. 2)

DETAILED REQUIREMENTS* FOR AVIATION GASOLINES*				DETAILED REQUIREMENTS FOR AUTOMOTIVE GASOLINES												
	GRADE 80	GRADE 100	GRADE 100 LL	ASTM TEST METHOD*	VOLATILITY CLASS					ASTM TEST METHOD	CLASS A	CLASS B	CLASS C	CLASS D	CLASS E	
KNOCK VALUE, MIN. OCTANE NUMBER, LEAN RATING	80	100	100	D 2700 <sup>c</sup>												OCTANE NUMBER, MOTOR METHOD
KNOCK VALUE, RICH RATING:																OCTANE NUMBER, RESEARCH METHOD
MINIMUM OCTANE NUMBER	87	130	130	D 909												OCTANE NUMBER, $\frac{RM}{2}$ (TABLE 3)
MINIMUM PERFORMANCE NUMBER <sup>1,2</sup>	87	130	130	D 2392												OCTANE NUMBER, $\frac{RM}{2}$ (TABLE 3)
COLOR <sup>3</sup>	RED <sup>4</sup>	GREEN	BLUE													OCTANE NUMBER, $\frac{RM}{2}$ (TABLE 3)
DYE CONTENT:																OCTANE NUMBER, $\frac{RM}{2}$ (TABLE 3)
PERMISSIBLE BLUE DYE <sup>5</sup> MAX., MG/GAL	0.5	4.7	5.7													OCTANE NUMBER, $\frac{RM}{2}$ (TABLE 3)
PERMISSIBLE YELLOW DYE <sup>5</sup> MG/GAL	NONE	5.9	NONE													OCTANE NUMBER, $\frac{RM}{2}$ (TABLE 3)
PERMISSIBLE RED DYE <sup>5</sup> MAX., MG/GAL	8.65	NONE	NONE													OCTANE NUMBER, $\frac{RM}{2}$ (TABLE 3)
TETRAETHYLEAD <sup>6</sup> MAX., ML/GAL	0.5 <sup>7</sup>	4.0	2.0	D 2547 OR D 2599 OR D 3341	0.05 (0.013) 4.2 (1.1)	0.05 (0.013) 4.2 (1.1)	0.05 (0.013) 4.2 (1.1)	0.05 (0.013) 4.2 (1.1)	0.05 (0.013) 4.2 (1.1)	0.05 (0.013) 4.2 (1.1)	0.05 (0.013) 4.2 (1.1)	0.05 (0.013) 4.2 (1.1)	0.05 (0.013) 4.2 (1.1)	0.05 (0.013) 4.2 (1.1)	0.05 (0.013) 4.2 (1.1)	LEAD CONTENT, MAX., G/GAL (GALILEO)
REQUIREMENTS FOR ALL GRADES:																
DISTILLATION TEMPERATURE <sup>8</sup> , °F (°C):																DISTILLATION TEMPERATURE <sup>8</sup> , °F (°C):
10% EVAPORATED, MAX., TEMP.	167 (75)	167 (75)		D 86												10% EVAPORATED, MAX. TEMP.
50% EVAPORATED, MIN. TEMP.																50% EVAPORATED, MIN. TEMP.
90% EVAPORATED, MAX., TEMP.	221 (105)	221 (105)														90% EVAPORATED, MAX. TEMP.
FINAL BOILING POINT, MAX., °F (°C)	275 (135)	275 (135)														90% EVAPORATED, MAX. TEMP.
SUM OF 10 AND 50% EVAPORATED TEMPERATURES, MIN.	338 (170)	338 (170)														END POINT, MAX.
DISTILLATION RECOVERY, MIN. %	97	97														
DISTILLATION RESIDUE, MAX. %	1.5	1.5														
DISTILLATION LOSS, MAX. %	1.5	1.5														
ACIDITY OF DISTILLATION RESIDUE	SHALL NOT BE ACID	SHALL NOT BE ACID		D 1093												
VAPOR PRESSURE, MAX., LB./IN. <sup>2</sup> (REID METHOD)	7.0	7.0														VAPOR/LIQUID RATIO <sup>9</sup>
NET HEAT OF COMBUSTION <sup>9</sup> MIN., BTU/LB	18,720	18,720														TEST TEMPERATURE, °F (°C)
COPPER STRIP CORROSION, MAX.	NO. 1	NO. 1														VAPOR/LIQUID RATIO, MAX.
POTENTIAL GUM, 15 HR. AGING GUM <sup>10</sup> MAX., MG/100 ML	6	6														VAPOR PRESSURE, MAX., PSI (AGA)
VISIBLY LEAD PRECIPITATE <sup>11</sup> MAX., MG/100 ML	3	3														(REID METHOD)
SULFUR, WT.%, MAX.	0.05	0.05														COPPER STRIP CORROSION, MAX.
FREEZING POINT, MAX., °F (°C)	-72 (-58)	-72 (-58)														EXISTENT GUM, MAX., MG/100ML
WATER REACTION																SULFUR, WT.%, MAX.
PERMISSIBLE ANTI-OXIDANTS <sup>12</sup> MAX., LB./1000 BBL (92 GAL)																LEADED
																UNLEADED
																OXIDATION STABILITY, MIN.

(footnotes for these specifications are on the following page)

TABLE 1. AVGAS AND AUTOGAS SPECIFICATIONS (ASTM TESTS D 910 AND D 439, REF. 2) (Continued)

Footnotes for autogas specifications ASTM D 439

- <sup>a</sup> At 760 mm Hg pressure (101.3 kPa).  
<sup>b</sup> The intentional addition of lead compounds is not permitted. Current EPA promulgations call for 0.05 g of lead per gallon (0.013 g/litre) maximum and 0.005 g of phosphorus per gallon (0.0013 g/litre) maximum, effective July 1, 1974.  
<sup>c</sup> See Table 3.

Footnotes for avgas specifications ASTM D 910

- <sup>a</sup> Requirements contained herein are absolute and are not subject to correction for tolerance of the test methods. If multiple determinations are made, average results shall be used.  
<sup>b</sup> The test methods indicated in this table are referred to in Section 9.  
<sup>c</sup> The values shown in Table 1 represent Aviation Method Ratings. Motor octane ratings obtained by ASTM Method D 2700 should be converted to aviation ratings by Conversion Table 2. If mutually agreed between the purchaser and the seller, Method D 614 may be used to obtain aviation ratings directly.  
<sup>d</sup> These colors have been approved by the Medical Director Chief, Division of Occupational Health, U.S. Department of Health, Education and Welfare.  
<sup>e</sup> If mutually agreed upon between the purchaser and the supplier, Grade 80 may be required to be free from tetraethyllead. In such a case, the fuel shall not contain any dye and the color as determined in accordance with ASTM Method D 156, Test for Saybolt Color of Petroleum Products (Saybolt Chromometer Method)<sup>2</sup> shall not be darker than +20.  
<sup>f</sup> The only blue dye which shall be present in the finished gasoline shall be essentially 1,4-dialkylamino-anthraquinone.  
<sup>g</sup> The only yellow dye which shall be present in the finished gasoline shall be essentially *p*-diethylaminoazobenzene (Color Index No. 11020).  
<sup>h</sup> The only red dye which shall be present in the finished gasoline shall be essentially methyl derivatives of azobenzene-4-azo-2-naphthol (methyl derivatives of Color Index No. 26105).  
<sup>i</sup> The tetraethyllead shall be added in the form of an antiknock mixture containing not less than 61 weight percent of tetraethyllead and sufficient ethylene dibromide to provide two bromine atoms per atom of lead. The balance shall contain no added ingredients other than kerosine, and an approved inhibitor, and blue dye, as specified, herein.  
<sup>j</sup> Use the value calculated from Table 1 in ASTM Method D 1405, for Estimation of Net Heat of Combustion of Aviation Fuels.<sup>3</sup> ASTM Method D 2382, Test for Heat of Combustion of Hydrocarbon Fuels by Bomb Calorimeter (High-Precision Method)<sup>4</sup> may be used as an alternative method. In case of dispute, Method D 2382 must be used. In this latter case, the minimum values for the net heat of combustion in Btu's per pound shall be 18,700 for Grades 80, 100, and 100LL.  
<sup>k</sup> Note that the temperature conversion for the sum is  $C_1 + C_2 = \frac{1}{9}(F_1 - 32 + F_2 - 32)$ .  
<sup>l</sup> If mutually agreed upon between the purchaser and the supplier, aviation gasoline may be required to meet at 16-h aging gum test (ASTM Method D 873, Test for Oxidation Stability of Aviation Fuels (Potential Residue Method)<sup>5</sup>) instead of the 5-h aging gum test. In such a case, the gum content shall not exceed 10 mg per 100 ml and the visible lead precipitate shall not exceed 4 mg per 100 ml. In such fuel the permissible antioxidants shall not exceed 8.4 lb per 1000 bbl (42 gal).  
<sup>m</sup> The visible lead precipitate requirement applies only to leaded fuels.  
<sup>n</sup> Permissible antioxidants are as follows:  
     *N,N'*-diisopropyl-*para*-phenylenediamine  
     *N,N'*-di-*secondary*-butyl-*para*-phenylenediamine  
     2,4-dimethyl-6-*tertiary*-butylphenol  
     2,6-ditertiary butyl-4-methylphenol  
     2,6-ditertiary butylphenol  
     Mixed tertiary butylphenols, composition:  
         75 percent 2,6-ditertiary butylphenol  
         10 to 15 percent 2,4,6-tritertiary butylphenol  
         10 to 15 percent *o*-tertiary butylphenol  
         72 percent min 2,4-dimethyl-6-*tertiary*-butylphenol, and 28 percent max monomethyl and di-methyl tertiary butylphenols.  
 These inhibitors may be added to the gasoline separately or in combination, in total concentration not to exceed 4.2 lb of inhibitor (not including weight of solvent) per 1000 bbl (42 gal).  
<sup>1</sup> Listing of and requirements for Grades 91-98, 108-135, and 115-145 appear in the 1967 version of this specification.  
<sup>2</sup> A minimum performance number of 130 is equivalent to a knock value determined using *isooctane* plus 1.28 ml TEL/gal (0.33 ml TEL/litre).  
<sup>3</sup> All performance numbers shall be reported to the nearest whole number.

TABLE 2. STATES WHICH DEFINE AUTOGAS PROPERTIES

	A	B	C
Considering the following			
eight major specification			
areas of ASTM D 439:			
Octane			
Sulfur			
Existent gum			
Copper strip corrosion			
Lead content			
Reid vapor pressure			
Vapor/liquid ratio			
Distillation			
Key:			
A - A state requiring all			
ASTM D 439 specs. or			
at least six of the			
above.			
B - A state requiring			
some ASTM D 439 specs.			
from one to five of			
the above.			
C - No requirement.			
(Data from Ref. 4)			
1. Alabama		x	
2. Alaska			x
3. Arizona	x		
4. Arkansas	x		
5. California	x		
6. Colorado		x	
7. Connecticut		x	
8. Delaware			x
9. Florida	x		
10. Georgia		x	
11. Hawaii	x		
12. Idaho	x		
13. Illinois			x
14. Indiana		x	
15. Iowa		x	
16. Kansas		x	
17. Kentucky			x
18. Louisiana		x	
19. Maine		x	
20. Maryland	x		
21. Massachusetts		x	
22. Michigan			x
23. Minnesota		x	
24. Mississippi	x		
25. Missouri		x	
26. Montana	x		
27. Nebraska			
28. Nevada		x	
29. New Hampshire			x
30. New Jersey			x
31. New Mexico		x	
32. New York		x	
33. North Carolina	x		
34. North Dakota		x	
35. Ohio			x
36. Oklahoma		x	
37. Oregon			x
38. Pennsylvania			x
39. Rhode Island			x
40. South Carolina	x		
41. South Dakota		x	
42. Tennessee	x		
43. Texas		x	
44. Utah		x	
45. Vermont			x
46. Virginia	x		
47. Washington			x
48. West Virginia			x
49. Wisconsin	x		
50. Wyoming		x	
51. District of Columbia			x



TABLE 3. STATES WHICH DEFINE AVGAS PROPERTIES

(Data from Ref. 4)

<u>State</u>	<u>Avgas Definition</u>
1. Colorado	ASTM specifications and definitions
2. Connecticut	Must be of United States Standard
3. Hawaii	. Any product conforming to the standards of ASTM D 910 (1970)
4. Minnesota	Defines avgas with a very loose specification, which could include most autogas
5. Nevada	Set by State Sealer of Weights and Measures, may be the same as ASTM D 910
6. North Dakota	Specifications on sulfur, Reid vapor pressure, cooper strip corrosion, potential gum, freezing point, octane, and distillation
7. Oklahoma	Specifications on distillation, Reid vapor pressure, octane, color, lead, and gum
8. South Dakota	Specifications on distillation, Reid vapor pressure, copper strip corrosion, and sulfur
9. Wyoming	Federal specifications and definitions

their performance in tests rather than by their actual composition. Performance specifications are a successful and practical method for controlling the performance of the product in the vehicle, while still allowing some variability of the composition of the product. Some of the most significant performance specifications are now considered in more detail in the following sections.

## PERFORMANCE REQUIREMENT SPECIFICATIONS

### OCTANE RATING.

Octane rating is a measure of a fuel's antiknock quality, that is, its ability to resist autoignition and preignition. These cause loss of power and efficiency, and can lead to the damage of engine parts. For these reasons, specifications exist for controlling the octane ratings of both avgas and avgas.

Regarding avgas, Grade 100 for example, is often expressed as 100/130 in which the first number is termed the Lean Aviation Rating and the second number is termed the Rich Rating Performance Number. This Rich rating is determined according to ASTM Test D 909 (2), which establishes the knock-limited power achieved for the given fuel under supercharged conditions. The Rich rating below 100 is the Supercharge octane number equal to the percent volume of isooctane in a blend of n-heptane which matches the knock intensity of the sample fuel. The Rich rating above 100 is given as mg/gal of tetraethyllead in isooctane, and is expressed as a performance number. Correlations are found in Table 1 of ASTM Test D 909 where, for example, the performance number for 1.28 ml/gal of tetramethyllead in isooctane is found to be equal to 130.

The Lean Aviation Rating is found according to ASTM Test D 2700 (2), which determines the knocking tendency of a fuel under standard operating conditions which are common to both automotive and aviation gasolines. This test yields the Motor octane rating, which below 100 is expressed at the percent volume of isooctane in a blend of n-heptane which matches the knock intensity of the sample fuel. For avgas, a Motor octane number above 100 is given as a performance number, and then converted into the Aviation Rating. Conversions for this expression are found in tables in the ASTM Tests D 909 and D 910 (2). Conversion equations for gasolines are as follows: (where "P.N." is "performance number" and "O.N." is "octane number").

For Motor P.N. less than 93 (i.e., less than 97.89 Motor O.N.):

$$\text{Aviation P.N.} = (1.08) (\text{Motor P.N.}) - 5.6 \quad (1)$$

For Motor P.N. greater than 93:

$$\text{Aviation P.N.} = 12.07 + (0.89) (\text{Motor P.N.}) \quad (2)$$

For octane numbers below 100:

$$P.N. = 2800 / (128 - O.N.) \quad (3)$$

For octane numbers above 100:

$$P.N. = 100 + (3) (O.N. - 100) \quad (4)$$

For automotive gasolines, the antiknock index is defined as the average of the Research method octane number and the Motor method octane number. The Motor method test is considered to be more severe than the Research method test due to the higher speeds and inlet temperature of the Motor method. Similar to avgas, the Motor octane number of autogas below 100 is the percent volume of isooctane in a blend of n-heptane which matches the knock intensity of the sample fuel. But, the Motor octane number above 100 is given as ml/gal of tetraethyllead in isooctane which matches the known intensity of the sample fuel.

The Research octane number for autogas is determined by the ASTM Test D 2699 (2). The values of this Research method octane number, above and below 100, are expressed in the same terms as those values of the autogas Motor method octane numbers, respectively.

In comparing avgas and autogas on the basis of octane ratings, no direct comparison can be made between the two fuels when considering the avgas Rich rating octane number versus the autogas Research method octane number. Not only are the tests run at different engine conditions, but the avgas test is run with rich mixtures, whereas the autogas test is run lean. As a result, the different hydrocarbon classes may be expected to rate differently on the two tests, especially for fuel of high aromatic content.

In analyzing this same subject, an Avco Lycoming report (6) of some gasoline inspection results showed the Aviation Motor octane numbers and the Rich rating octane numbers of five various autogas samples. The resulting ratings varied greatly between the gasolines. For example, the lowest rated sample had an Aviation Motor octane number of 84.0 and a Rich rating octane number of 90.9. In contrast, the highest rated sample had an Aviation Motor octane number of 94.7 and a Rich rating octane number of 126.4. Therefore, all of these samples satisfied the octane requirements of grade 80/87 avgas. However, they were considerably below the requirements of the higher grades of avgas.

A 1976 Exxon letter of C. T. Stone (7) states that tested samples of their unleaded autogas indicated a Rich octane number of 88 to 89, which also meets the requirement of 80/87 avgas octane ratings. This letter further emphasized though that in the future, samples may not meet this requirement since no control of this characteristic is exercised on autogas.

The situation therefore still remains that no comparison can be made between autogas and avgas when considering the Rich rating octane number. In reviewing the limited

data available an obvious need appears for a general correlation to be made for fuels of various hydrocarbon classes in order to assure that autogas possesses sufficient octane quality to satisfy the rich rating for grade 80/87 avgas.

In considering the avgas Lean rating octane number, this rating is very close to the Motor method octane rating of autogas, and has been correlated with it formally according to equations (1) - (4). Some typical values are:

80 Aviation number = 80 Motor octane number

100 Aviation number = 99.7 Motor octane number

### DISTILLATION.

Distillation is a measure of the relative volatility of fuels. The lower the temperature is for a given percent evaporation, the greater the volatility is at that point. The standard ASTM test for this distillation is D 86 (2). Considering now a distillation curve, the low evaporation region or "front end" is considered to represent the relative starting quality of the gasoline. The lower the front end temperature, the easier the starting. The ASTM specifications contain five volatility classes (A through E) for automotive gasoline, of which class E is the best for cold weather starting. The starting characteristics of the different classes get progressively poorer from E through A. The front end distillation temperature is also an indicator of the relative vapor lock tendency of the fuel, although the Reid vapor pressure and the vapor/liquid ratio are considered to be better vapor lock indicators than this 10% point region. Also, the front end temperature indicates relative evaporation tendencies of fuels, where again the lower temperature of the 10% point would imply greater evaporation losses.

In regards to higher percent evaporation points, the 40%-70% evaporation range is considered indicative of the engine warm-up characteristics resulting from the fuel in question.

Considering now the 90% evaporation region or "back end," a low back end distillation temperature may possibly result in increased deposits and poor fuel distribution. This relative potential for increased deposits refers to cylinder deposits and spark plug fouling. The back end also gives a relative indication of the oil dilution and smoky combustion tendency of the fuel. This characteristic is due to the fact that some high temperature boiling components in the gasoline may reach the cylinders in liquid form if the fuel volatility is too low. This phenomenon could cause cylinder wall washing and oil dilution if liquid fuel flows past the rings.

Within the petroleum industry, the sum of the (10% temp.) + (50% temp.) + (90% temp.)/5 is often used informally as an index of the relative carburetor icing tendency of a fuel. In automotive applications a carburetor icing problem may arise if this sum is less than 390°F.

These above points regarding the distillation curve values of a fuel demonstrate the importance of distillation temperature values relating to engine performance characteristics. Some of these performance characteristics pertain to serious safety problems and therefore specifications governing these fuel properties are important to know. Figure 1 portrays the relationship between automotive engine performance and the ASTM curve. No comparable correlation has been made for aircraft engines, although the outcome may be expected to be similar.

Specifications for the distillation properties of autogas and avgas are listed in Table 1. The maximum distillation specifications are also plotted in Figure 2. Inspection of this figure shows a lower 10% evaporation point temperature specified for autogas than for avgas, especially that of autogas volatility class E. This figure also shows the much higher back end of the distillation curve specified for autogas than that of avgas.

With the distillation curve characteristics, some of which are mentioned above, one can clearly see how avgas is specified such that it should have, for example, less deposit-forming potential, less carburetor icing tendencies, and less relative vapor lock tendencies than autogas. This figure also shows a characteristic of much easier starting of autogas volatility class E than that of avgas.

#### VOLATILITY.

The volatility of a fuel is its tendency to evaporate or to change from a liquid to a gaseous state. The ASTM distillation curve is one measure of the relative volatility of fuels. Reid vapor pressure is a front end volatility indicator. It is measured at 100°F (37.8°C, and is essentially equal to the vapor pressure. Compared to ASTM distillation, the Reid vapor pressure and the vapor/liquid ratio are more specific measures of the front end volatility and the vapor lock tendency of a fuel. This characteristic of the fuel is very important for aircraft applications. Reid vapor pressure is also a good measure of the relative evaporative loss tendency of a fuel. Given two gasolines with approximately the same distillation curves, but different Reid vapor pressures, the fuel with the higher vapor pressure will tend to develop vapor lock more readily.

ASTM specifications require a maximum Reid vapor pressure of 7.0 psi for aviation gasoline, and a range from 9.0 to 15.0 psi for automotive gasolines (2), which is divided into the five volatility classes. Although not specified in ASTM D 910 the minimum Reid vapor pressure for aviation gasolines is controlled by the refinery not to be less than 5.5 psi (41). Both avgas and autogas volatility are seasonally adjusted with the highest values in the coldest ambients. It may be noted that this minimum R.V.P. for autogas of about 7 is the maximum permitted for avgas. In general, considerable variability exists as Figure 6 indicates.

The vapor/liquid ratio of a gasoline is the ratio, at atmospheric pressure, of the volume of vapor formed to the volume of the liquid sample. Gasolines may have identical Reid vapor pressures, but yet their vapor forming characteristics (V/L

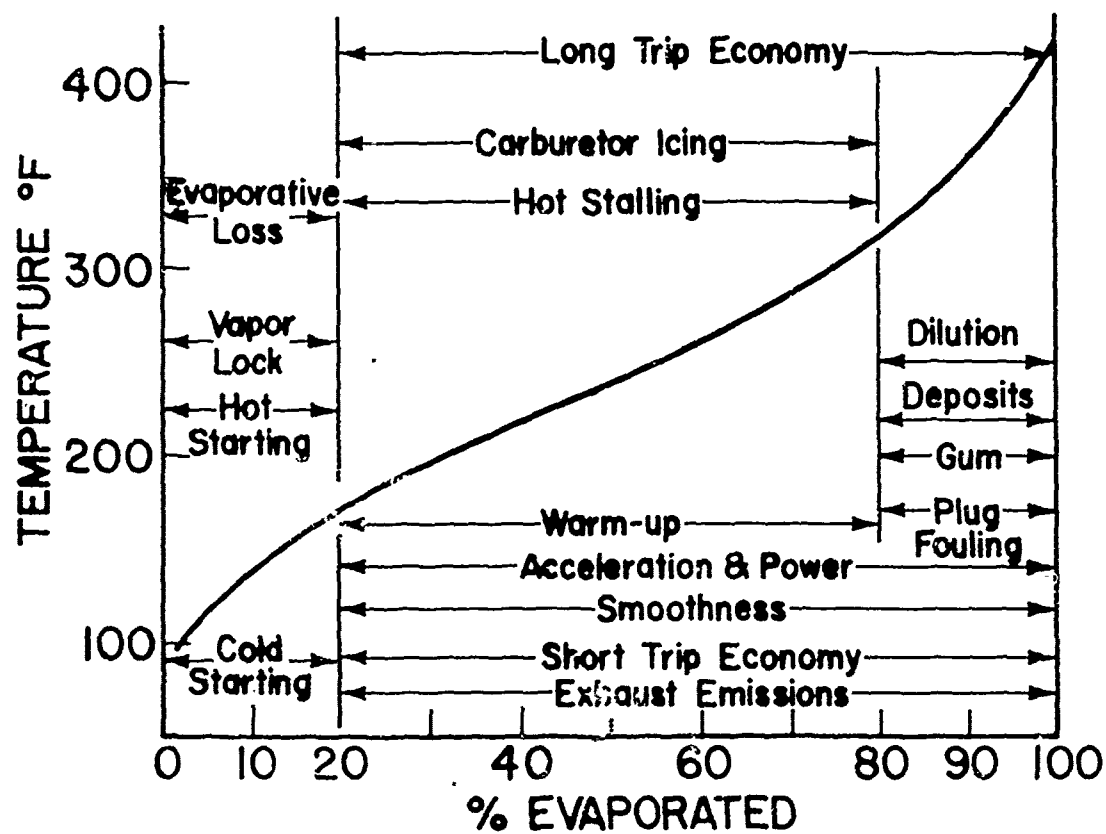
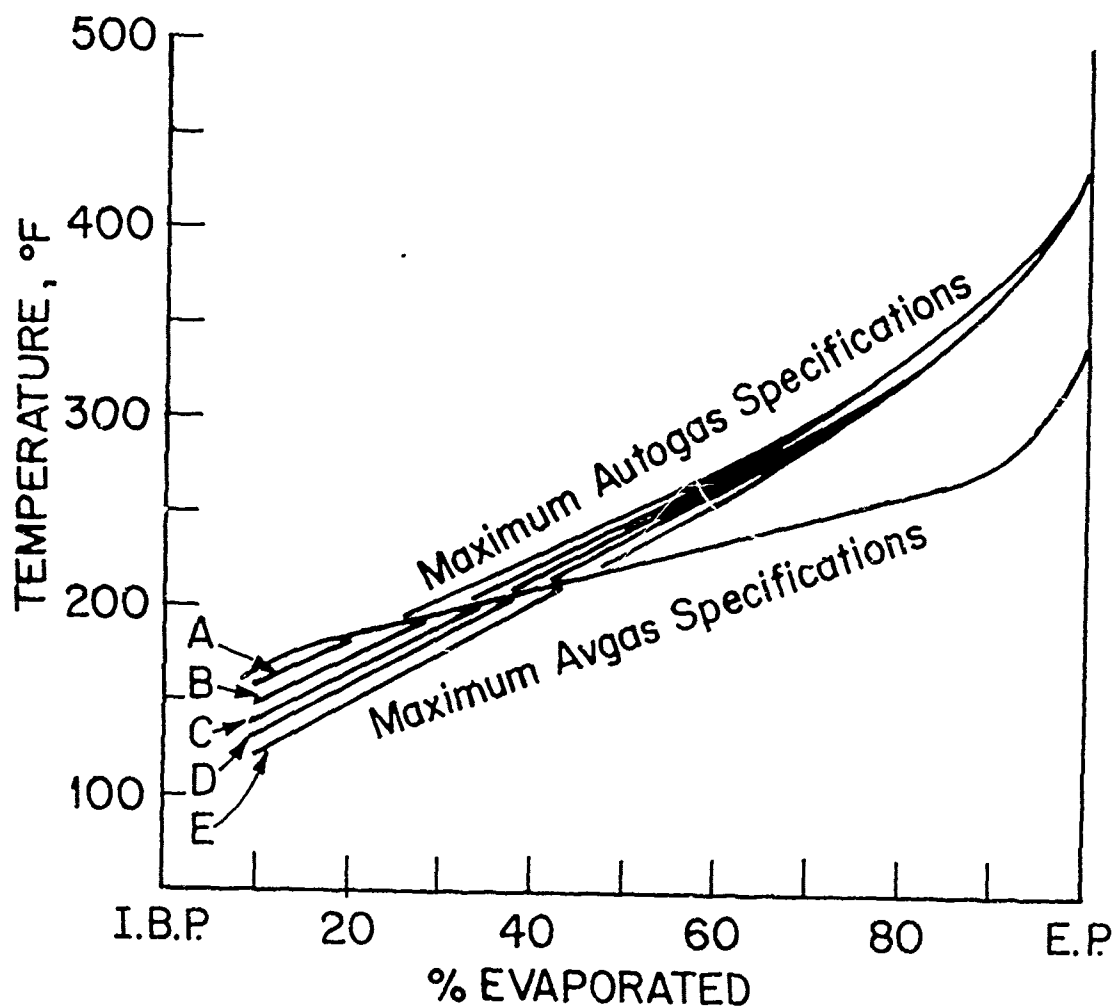


FIGURE 1. RELATIONSHIP BETWEEN A TYPICAL AUTOGAS ASTM DISTILLATION CURVE AND ENGINE PERFORMANCE (REFERENCE 10)



Avgas: maximum specifications from ASTM D 910 (Ref. 2)

Autogas: maximum specifications from ASTM D 439 (Ref. 2)

- A - Volatility Class A
- B - Volatility Class B
- C - Volatility Class C
- D - Volatility Class D
- E - Volatility Class E

FIGURE 2. MAXIMUM ASTM DISTILLATION REQUIREMENTS FOR AVGAS AND AUTOGAS

ratios) may be different because one fuel may have a lower distillation curve than another. ASTM specifications D 439 for automotive gasolines do have vapor/liquid ratio requirements, whereas the ASTM aviation gasoline specifications do not. This is because the tight specifications on avgas make a vapor/liquid ratio specification redundant. It is well to note that automotive systems are commonly designed to handle V/L ratios up to 20, whereas some aircraft develop vapor lock problems with V/L ratios slightly greater than one.

#### COMPOSITION.

Gasolines are made from crude oils whose properties and composition may vary considerably. Crudes may be as thin and colorless as water, or as thick and black as liquid tar. Crude oil is a mixture of thousands of hydrocarbons. The hydrocarbons are classified as paraffins, olefins, naphthenes, and aromatics.

High octane number is associated with small and compact molecules, aromatics such as toluene and xylenes or branched paraffins such as isooctane. Paraffins produce less carbon deposits than aromatics. Paraffins have the highest heating value per unit mass due to high percentage of hydrogen in the molecule. Paraffins have the least octane number sensitivity\* of the four hydrocarbon groups. Olefins have a higher sensitivity and a lower octane rating than paraffins. Autogas often contains a much higher quantity of olefins than avgas which makes them less stable in storage than avgas (8). Aromatics have a relatively high sensitivity. They also have high self-ignition temperatures as compared to straight chain hydrocarbons. Aromatics tend to produce smoke when burned, and are major contributors to combustion chamber deposits. Aromatics contain much less energy per unit weight than paraffins, and therefore the amount contained in aviation gasoline usually does not exceed 20% by volume (8). Inspection of Table 1 shows that avgas has a Btu/lb heating value specification, whereas autogas does not. This heating value specification therefore limits the aromatic content of avgas to a much lower value than that of autogas (41,42).

Sulfur is found in gasoline as either free sulfur or hydrogen sulfide. In the combustion process, sulfur will also unite with oxygen to form sulfur dioxide and some small fraction forms sulfuric acid in the presence of combustion generated water. This sulfuric acid corrodes engine parts including rings and cylinder bores. A portion of this sulfur is known to combine with TEL forming lead sulfates which reduces the antiknock quality of the mixture. These potential problems with sulfur show why a sulfur specification is important, and ASTM specifications are much stricter regarding sulfur content for avgas than for autogas. For example, as shown in Table 1, ASTM specification D 910 for avgas allows only a maximum of 0.05% by weight of sulfur, whereas ASTM specification D 439 for autogas allows a maximum of 0.10% and 0.15% by weight of sulfur present for unleaded and leaded autogas, respectively, even though the national average autogas is about 0.03% (11). Sulfur in

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\*Sensitivity is defined as the difference between the Research octane number and the Motor octane number.



fuels is also controlled through federal, state and local regulations, primarily for air pollution considerations (9). Various dyes are also specified to be added to gasoline, though merely for visual identification purposes.

In considering water in gasoline, the ASTM test D 1094 (2) determines the presence of water-miscible components in aviation gasoline and the effect of these components on the fuel-water interface. A separate water phase can be found as a result of a temperature decrease when enough water is present in the fuel. In some cases, water freezes in finely dispersed crystals and plugs fuel filters. In other cases, ice crystals accumulate and plug the fuel line. When water is found in the fuel, it is often the result of condensation which arises naturally in the thermal cycle. Some of this water may find its way to the fuel pump where, in the presence of sulfur or acidic conditions, it can attack zinc castings or coatings of the fuel system. The resulting corrosion may form a deposit which could interfere with the proper operation of the carburetor. Water reaction is therefore important in the consideration of aviation gasolines. ASTM has a water reaction regulation for aviation gasolines, but not for automotive gasolines. In light aircraft operation it is a practice to drain tank bottoms prior to use of the aircraft to minimize fuel line freezing problems. In cold ambients automotive gasolines commonly contain anti-icers to alleviate this problem.

#### ADDITIVES.

An additive is a chemical compound added to a fuel to create certain desirable properties of that fuel or eliminate another undesirable property. For gasolines, any compound added in quantities of 5% or less is termed an "additive." Greater amounts are termed blending agents. Many additives are used at a level of a few parts per million by weight.

Below are some important additives (or additive groups) typically found in gasoline and not previously discussed.

- Phosphorus compounds—these are added to reduce glowing deposits and spark plug fouling
- Tetraethyllead—this is added to increase fuel octane
- Scavengers—these are added to chemically remove the otherwise non-volatile lead products from the combustion chamber
- Antioxidants—these are added to reduce gum formation

In regard to additives in autogas, the Environmental Protection Agency regulates the maximum amount of lead and phosphorus (5). Also required is that all fuels and fuel additives must be registered with EPA. The reason for this registration is for emission control and for the protection of emission control devices on vehicles. ASTM D 459 has no specifications on additives in autogas. ASTM D 910 specifications for avgas does specify a maximum amount of tetraethyllead and its scavenger

ethylene dibromide. It also requires identifying dye and antioxidants. A list of permissible antioxidants is also given. A more detailed analysis of additives follows later in this report.

#### STABILITY.

Stability of a gasoline is its ability to maintain its antiknock properties and to resist gum formation.

Gum, peroxides, and insoluble precipitates may form when the unstable hydrocarbons (for example, olefins) oxidize or combine with each other by a type of polymerization, forming viscous liquids or solids. As noted in the composition section, automotive gasolines contain more olefins (8), therefore making them less stable in storage than avgas. In contrast to avgas, autogas is not expected to undergo storage much beyond six months unless it is fortified with higher levels of antioxidants (39). Autogas stored for several months may decrease in octane rating and form gum (3). Avgas, on the other hand, is expected to be stored for longer periods and is appropriately formulated.

Testing a gasoline for actual gum content at the refinery is required for autogas, according to ASTM D 439. Gums form with time, and high temperatures. Copper-containing materials and tetraethyllead are catalysts for gum formation. Avgas may age quite a while in the field before being used. The gum present at the time of use after aging is thus very important. ASTM D 910 has a potential gum, not existent gum, specification for avgas, as can be seen in Table 1. This potential gum test not only measures existing gum, but measures the potential of the fuel to form gum in the future also. Recently a test called Oxidation Stability (ASTM D 525) which is similar to, but not identical to the potential gum test of avgas, was added to ASTM D 439 for autogas. Therefore the stability specifications for autogas and avgas are now more similar. Given just a small tightening of these autogas requirements, both fuels would be almost the same with respect to stability specifications.

#### DEPOSIT CHARACTERISTICS.

A high back end distillation temperature range (10) and high gum content indicate potential combustion chamber, piston ring groove, lower crankcase, and valve stem deposits. Gum deposited on intake valve stems may contribute to intake valve sticking. ASTM specifications for avgas require relatively low temperatures at the back end of the distillation curve. The previous section on stability pointed out the differences in gum specifications for autogas and avgas.

Deposits are also related to the aromatic content of the fuel. A higher aromatic content indicates potentially more deposits. A low heating value per pound of fuel is an indication of higher aromatic content. ASTM L 910 has a specification for the heating value of avgas, but not for autogas, and this effectively limits aromatic contents, as was discussed previously.

Tetraethyllead, contributes greatly to deposits in engines. To scavenge out the lead compounds, avgas typically contains one theory of ethylene dibromide, whereas autogas contains one theory of ethylene dichloride and 1/2 theory of ethylene dibromide. (A theory is the theoretical amount required to combine with the lead additive.) Ethylene dibromide is more effective for high temperature operation, whereas ethylene dichloride is better at lower temperatures. ASTM specifies two bromine atoms per atom of lead for avgas, but no specification for autogas.

#### EXTENT OF SOME RELEVANT MANDATORY REQUIREMENTS

The U.S. Clean Air Act requires the registration of all fuels and fuel additives and concentrations of the additives. This is accomplished through the Environmental Protection Agency. The EPA closely regulates the lead content in automotive gasolines. It also requires that each retail outlet must sell at least one grade of unleaded gasoline of not less than 91 research octane number, and it provides for a decrease in this octane number requirement with altitude. The EPA also regulates fuel dispenser nozzle diameters and requires two "unleaded gasoline only" labels on each vehicle with catalytic converter emission control devices (5).

The Federal Trade Commission has procedures for determining, certifying, and posting on the fuel dispenser the octane rating of automotive gasoline intended for sale to consumers (5).

#### FAA REQUIREMENTS.

The Federal Aviation Administration has requirements (5) for the certification of aircraft and aircraft engines. For engine certification, the applicant must designate the fuel, lubricant and hydraulic fluid that may be used in the engine. It is at this step where a grade of avgas is usually specified as the fuel. Engine ratings and operating limitations are established by the Administrator according to various criteria which include the engine fuel and oil grades or specifications. The FAA also requires that each engine type be tested; one test of which is the "Detonation Test." This is to establish that the engine can function without detonation throughout its range of intended conditions of operation. Other aircraft engine requirements cover design and construction, for example that the engine must supply an appropriate mixture of the fuel to the cylinders throughout the complete operating range of the engine under all flight and atmospheric conditions. Another such requirement is that each passage in the induction system which conducts a mixture of fuel and air must be self-draining. This prevents a liquid lock in the cylinders.

For the aircraft certification the FAA requires the fuel grade be established so that it is not less than that required for the operation of the engine within the limitations of specified takeoff and continuous operations. The FAA also requires

the fuel filter openings be marked with the minimum fuel grade. Regarding the fuel system, the FAA also requires that each fuel system must be free from vapor lock when using 110°F fuel under critical operating conditions. In addition to this requirement, each fuel system must be constructed and arranged to insure a flow of fuel at a rate and pressure established for proper engine functioning under each likely operating condition, including any maneuver for which certification is requested. Also regarding fuel flow, the ability of the fuel system to provide fuel at the rates specified (in the section 23.955, subpart E) and at a pressure sufficient for proper carburetor operation must be shown in the attitude that is most critical with respect to fuel feed and quantity of unusable fuel (5).

#### STATE REQUIREMENTS.

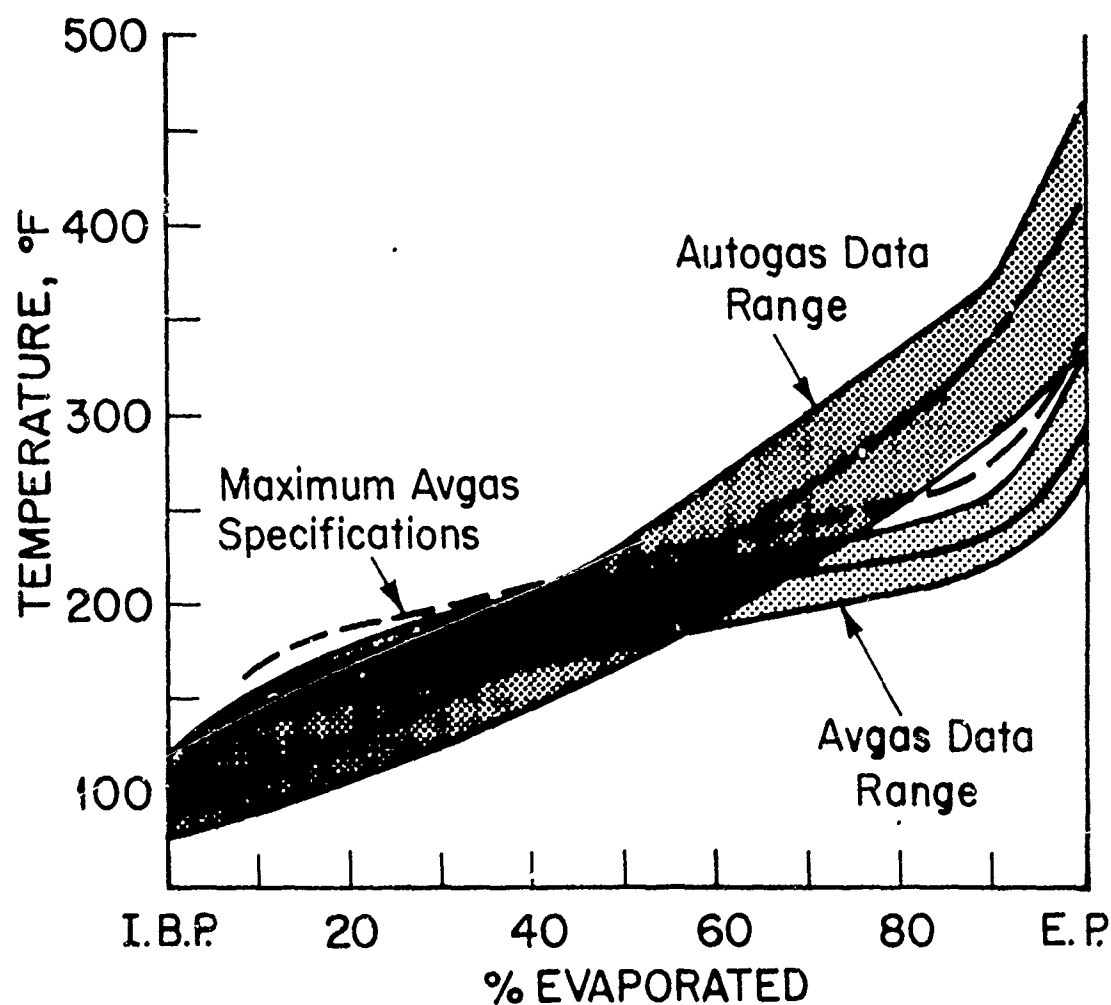
More specific mandatory regulations of gasolines and their properties are on the state level. According to the "Digest of State Inspection Laws Relating to Petroleum Products" (4), some states require that these automotive gasolines meet all the requirements of ASTM specification D 439. Some states require different maximum and minimum values for some properties determined by the various autogas tests. Some states require only a few tests and some states have no inspection laws regarding petroleum products, as Table 2 reveals. As mentioned before, nine states have a definition for avgas covering such characteristics as distillation, octane number, lead content and gum content. Table 3 shows which states have such a definition.

#### GASOLINE VARIABILITY IN THE UNITED STATES

Twice a year, summer and winter, the Department of Energy tabulates data on the performance properties of autogas. The Appendix to this report contains six tables (Table A-1 through Table A-6) of data taken from these Department of Energy reports for winter of 1978-79 and summer of 1979 (11,12).

Inspection of these tables reveals a wide range of autogas properties between the 17 different districts across the nation, and often a wide variation within each district itself. Figures 3 through 8 were constructed using data available for avgas, the winter of 1978-79 Department of Energy autogas survey, and the summer of 1979 Department of Energy autogas survey. The 80/87 avgas data of the 1969 survey (13) is in Table A-7. 1969 is the last year for which avgas survey data is available.

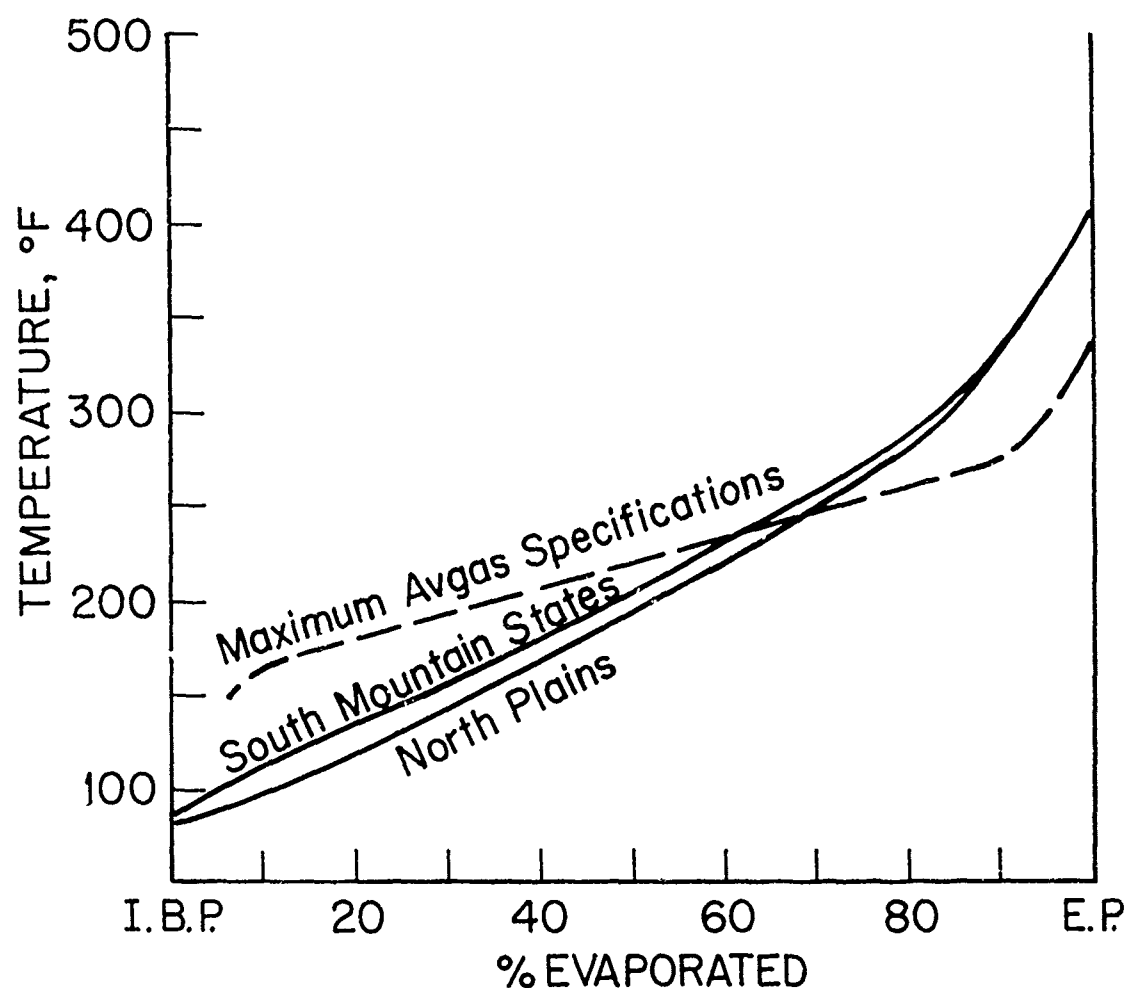
Figure 3 shows the national average distillation curve for winter of 1978-79 regular autogas, along with curves of the maximum and minimum values of this winter regular autogas. This band demonstrates a wide range of volatilities of regular winter autogas throughout the nation. Also shown on Figure 3 is the same band for 80/87 avgas, from the 1969 data (13). This avgas band demonstrates a much narrower range



80/87 avgas maximum specifications from ASTM D 910 (Ref. 2); maximum, average, and minimum distillation data from the Bureau of Mines survey of 1969 (Ref. 13)

Regular autogas maximum, average, and minimum distillation data from D.O.E. surveys of the winter '78-'79 and the summer '79 (Refs. 11,12)

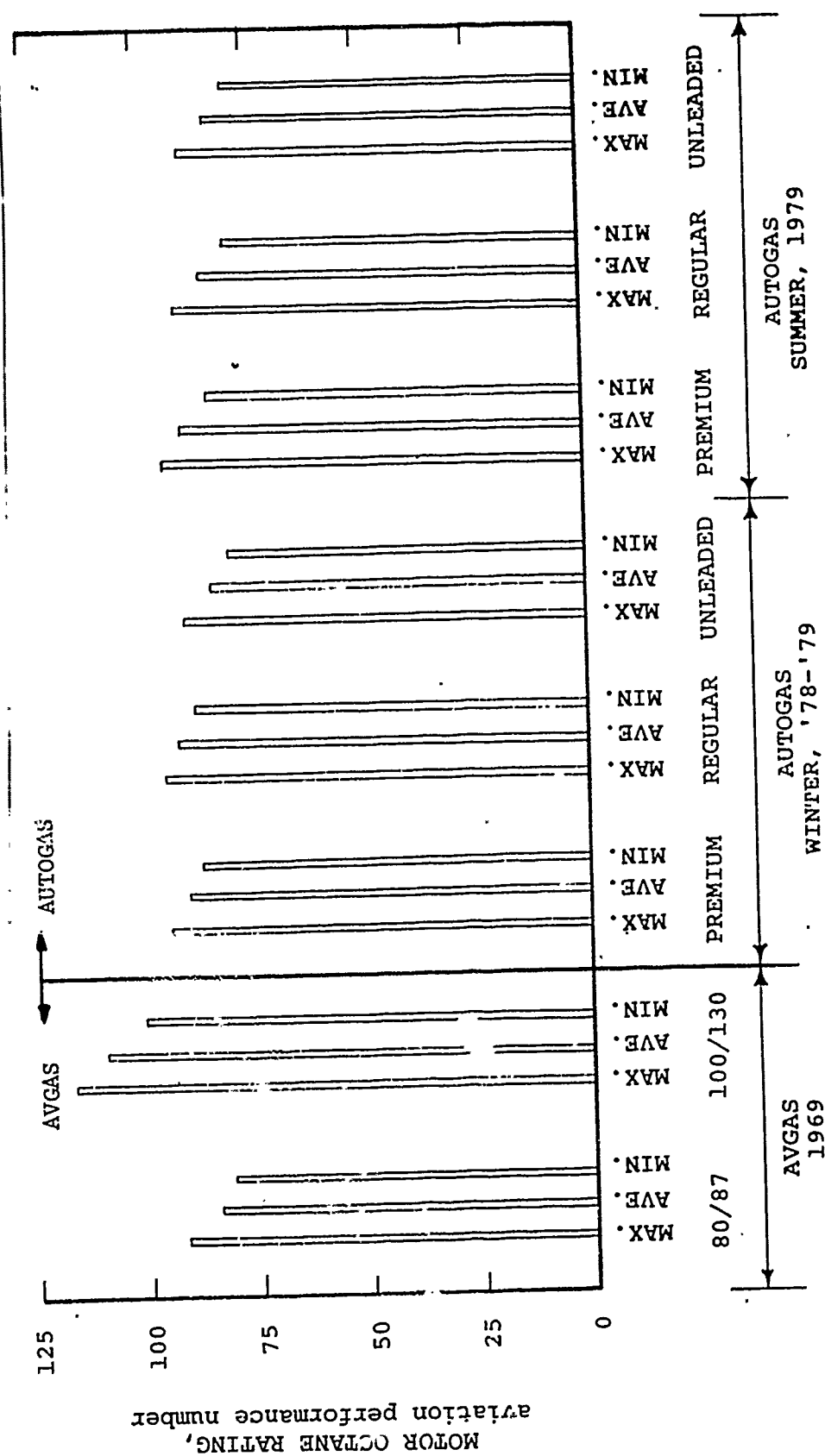
FIGURE 3. COMPARISON OF ACTUAL 80/87 AVGAS AND REGULAR AUTOGAS DISTILLATION DATA FROM SURVEYS WITH THE MAXIMUM AVGAS DISTILLATION REQUIREMENTS OF ASTM



Avgas maximum specifications from ASTM D 910 (Ref. 2)

Regular autogas data of the North Plains and South Mountain States districts from D.O.E. surveys of the winter '78-'79 (Ref. 11)

FIGURE 4. COMPARISON OF AVERAGE DISTILLATION DATA FROM SURVEYS OF REGULAR AUTOGAS FOR TWO DIFFERENT DISTRICTS OF THE U.S. DURING THE WINTER '78-'79 WITH THE MAXIMUM AVGAS DISTILLATION REQUIREMENTS OF ASTM

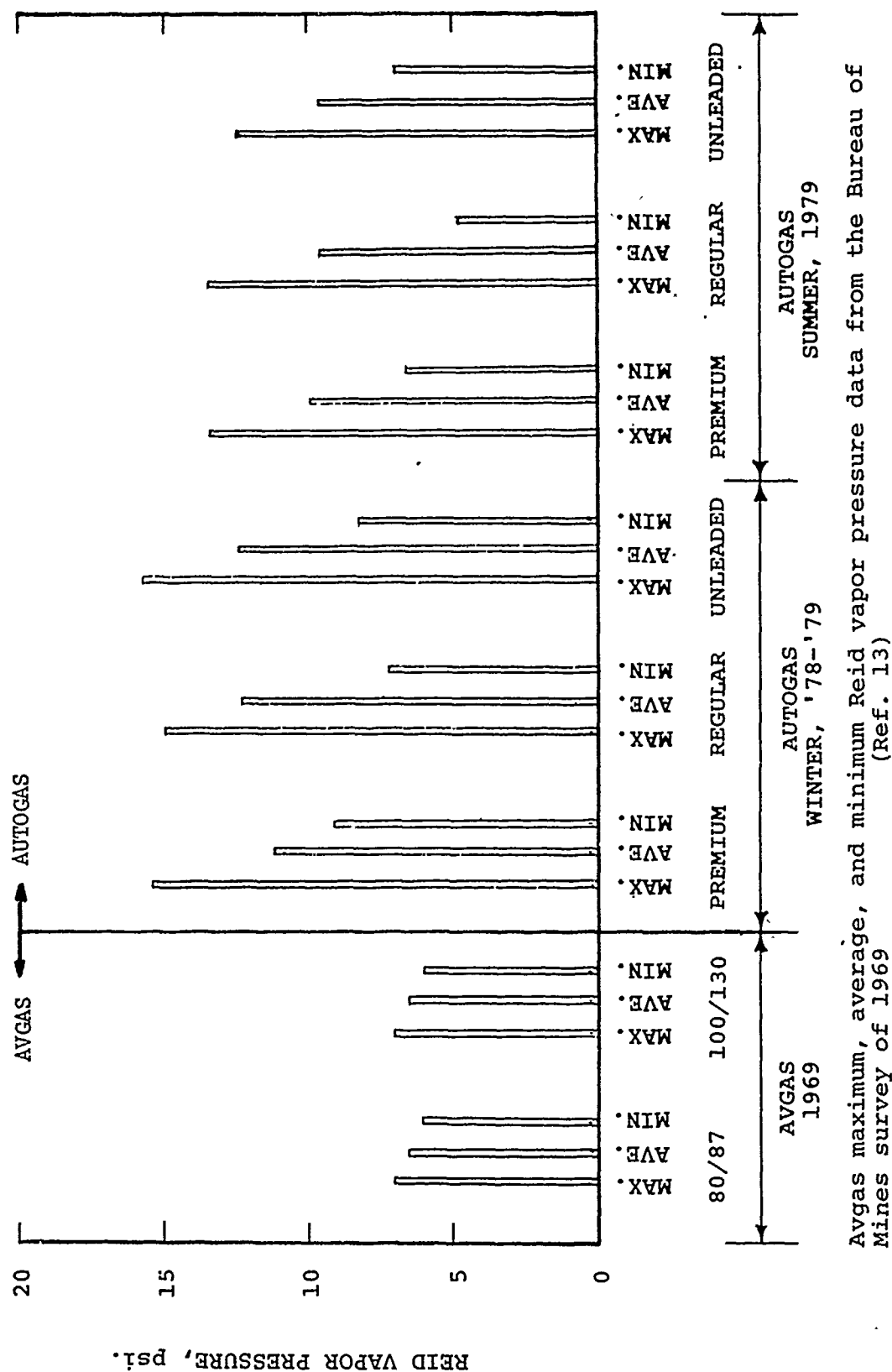


Avgas maximum, average, and minimum Motor octane ratings from the Bureau of Mines survey of 1969 (Ref. 13)

Autogas maximum, average, and minimum Motor octane ratings from the D.O.E. surveys of the winter '78-'79 and the summer '79 (Refs. 11,12)

(Table 2 in ASTM D 910, (Ref. 2) was used to convert the autogas values to aviation performance numbers.)

FIGURE 5. COMPARISON OF ACTUAL AVGAS AND AUTOGAS MOTOR OCTANE RATING DATA FROM SURVEYS

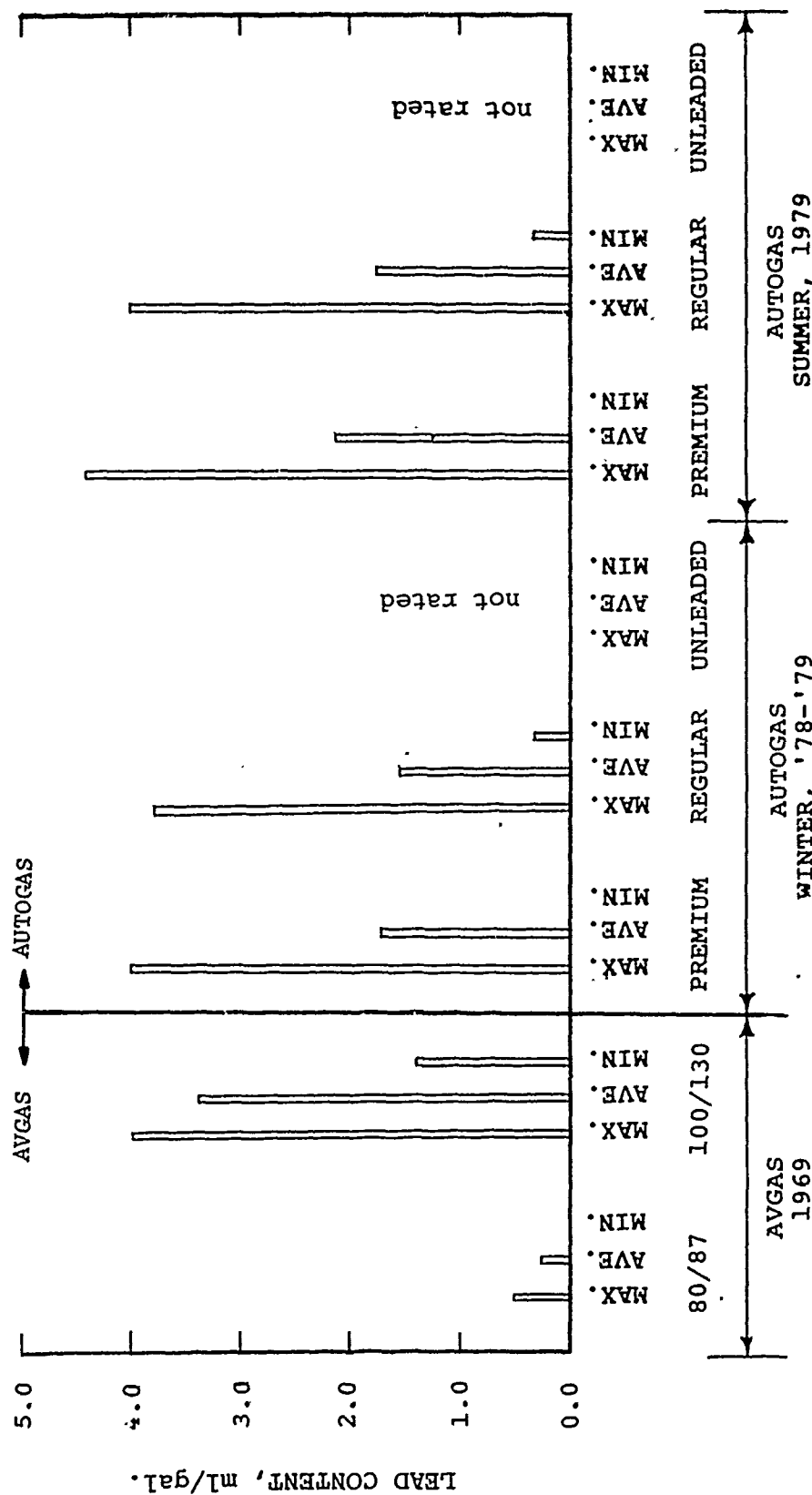


Avgas maximum, average, and minimum Reid vapor pressure data from the Bureau of Mines survey of 1969

Autogas maximum, average, and minimum Reid vapor pressure data from the D.O.E. surveys of the winter '78-'79 and the summer '79 (Refs. 11,12)

FIGURE 6. COMPARISON OF ACTUAL AVGAS AND AUTOGAS REID VAPOR PRESSURE DATA FROM SURVEYS





Autogas maximum, average, and minimum lead content data from the Bureau of Mines survey of 1969 (Ref. 13)

Autogas maximum, average, and minimum lead content data from the D.O.E. surveys of the winter '78-'79 and the summer '79 (Refs. 11,12)

(Considering all lead in autogas to be tetraethyllead, the units of g/gal. were converted to ml/gal. using the relationship: (g/gal.) (0.946) = (ml/gal.) for the autogas lead content.)

FIGURE 7. COMPARISON OF ACTUAL AVGAS AND AUTOGAS LEAD CONTENT DATA FROM SURVEYS

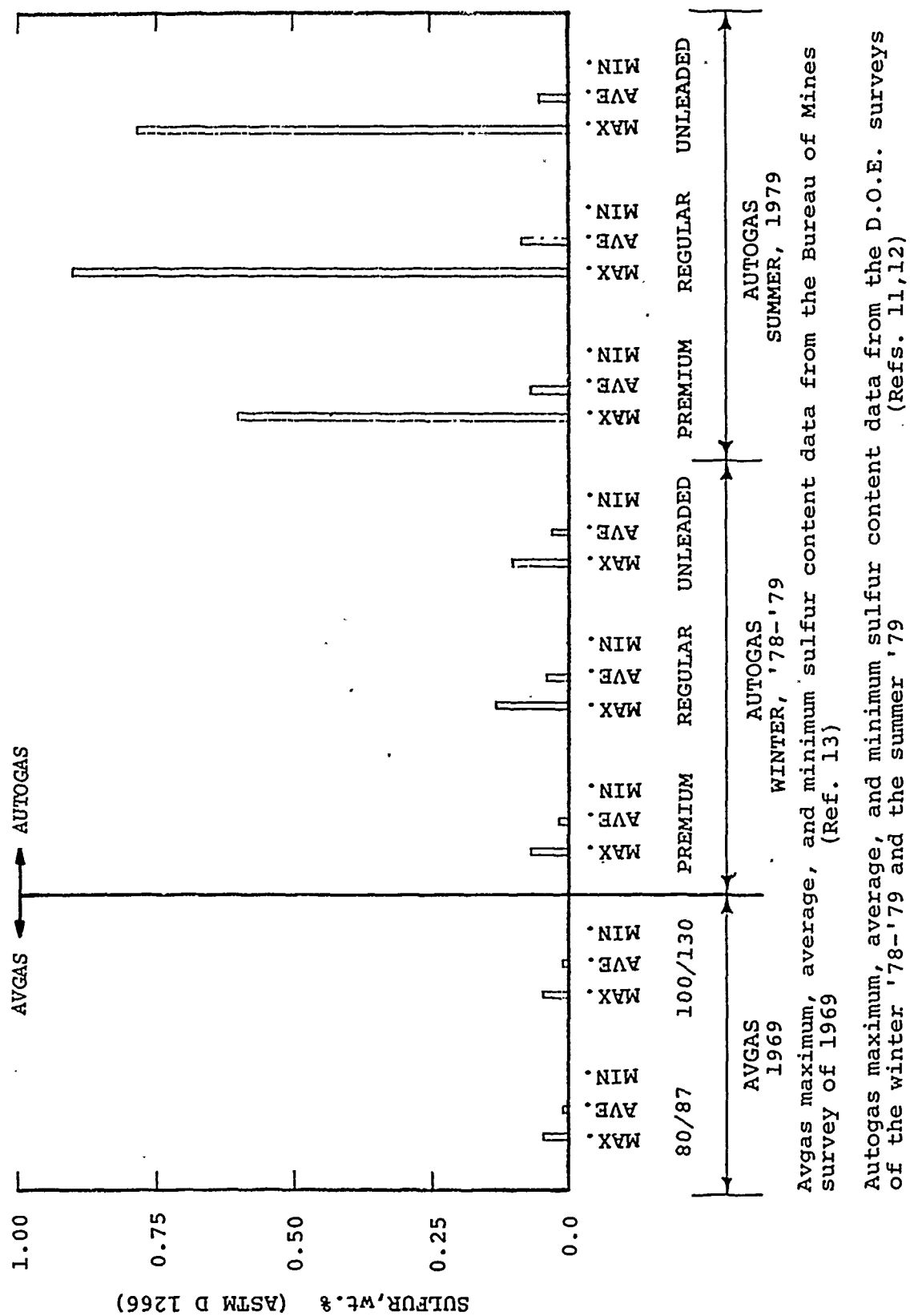


FIGURE 8. COMPARISON OF ACTUAL AVGAS AND AUTOGAS SULFUR CONTENT DATA FROM SURVEYS

of volatilities of avgas across the nation than that of autogas.

Figure 4 shows average distillation curves for 1978-79 winter regular autogas taken from two different districts. These curves demonstrate a difference between the South Mountain States district and the North Plains district of about two volatility classes in the front end distillation range, during the same season.

Tables A-1 through A-6 and Figures 5 through 8 show large variations in gasoline properties also existing between summer and winter autogas, depending on location.

For example, considering unleaded gasoline; the national maximum Reid vapor pressure was in Michigan (district 5) in the winter of 78-79, and was 15.6 psi. The minimum Reid vapor pressure was in the Mid-Atlantic coast region (district 2) in the summer of 1979, and was 7.0 psi. Inspection of Figure 6 shows this comparison easily. This example demonstrates a substantial variation of a critical performance characteristic of autogas across the country throughout the year.

Figure 5 shows some decrease in average octane rating of regular autogas for the summer of 1979 from that of the previous winter, though these ratings are quite similar. But, Figure 7 shows very large variations of lead content in autogas for both summer of 1979 and the previous winter, especially with premium autogas. This figure also shows a large variation of lead content for 100/130 avgas of 1969. In addition to lead content, large variations in sulfur contents of some autogas are shown in Figure 8.

An important point to be considered here with Tables A-1 through A-6 and Figures 3 through 8 is that for the 80/87 avgas data, only 24 samples were used whereas for the summer of 1979 autogas, 1,001 samples, 955 samples, and 445 samples were used for the unleaded, regular and premium gasolines, respectively. But, Tables A-1 through A-6 show that in the individual districts, ranges of values of the various properties are still quite large for a much smaller number of samples. Therefore one conclusion is that autogas performance characteristics vary greatly within the same district at the same time of year, and between different districts at the same time of year, as well as at different times of the year.

In contrast to the widespread variation of some performance characteristics of autogas, avgas typically has a relatively small spread of values. For 1969, Figure 6 shows that both the 80/78 and 100/130 avgas had maximum Reid vapor pressures of 7.0 psi, and minimum values of 6.0 psi. This is a spread of 1.0 psi R.V.P. for avgas compared to a spread of 8.6 psi for unleaded autogas. Also, the spread of Reid vapor pressure values of regular gasoline was 10.1 psi (from 4.8 to 14.9), and the spread of those values for premium was 8.6 psi (from 6.7 to 15.3).

## WHICH AVGAS CAN BE REPLACED BY AUTOGAS AND WHY

Based on data from the U.S. Department of Energy (11,12) a comparison of all automotive gasolines (unleaded, regular, and premium) with grades 100/130 and 100 LL aviation gasoline on the basis of motor octane numbers shows that automotive gasolines, with their range of Motor octane numbers of 84 to 90, fall far short of the required 99.6 Motor octane number of each of the 100 grade aviation gasolines, and precludes use of autogas as a substitute for those grades or higher grades.

In comparing automotive gasolines with grade 80/87 avgas, the automotive gasolines appear to exceed the aviation requirement for the Lean octane rating. Some question exists as to whether the automotive gasolines would meet the Rich octane number requirement. Therefore considering octane quality only, grade 80 avgas is the only grade which might be replaced by autogas, a topic to be considered in much more detail in the remainder of this report. The preceding sentence is not intended to mean that autogas can replace 80/87 avgas, since additional characteristics must be considered. These characteristics are discussed in detail in the balance of this report.

## DETAILED DISCUSSION OF POTENTIAL PROBLEM AREAS

### COMBUSTION PROBLEMS.

KNOCK. Knock is a spontaneous combustion of part of the fuel-air mixture resulting in rapid gas pressure oscillations. Knock continuing even over a relatively short period of time in an aircooled engine can lead to engine damage. The pressure fluctuations cause a large amount of heat transfer to the piston and combustion chamber. In an aircooled engine, which is very limited in its ability to remove excess heat, a hot spot is likely to form at an overheated valve or spark plug. If the hot spot is in the range of 1600-1765°F preignition can occur and cause rapid piston failure (15,16). Because of the high noise level in most light aircraft, knocking and/or preignition are not always audible. Therefore it is important to make sure that the fuel has a high enough octane number so that knock will not occur under any condition.

The Motor Gasoline survey published by the U.S. Department of Energy (11,12) indicates the Motor octane numbers for the three grades of autogas (regular, lead free and premium) are high enough to satisfy the aviation lean mixture octane requirements of those engines designed to use 80/87 avgas, at least when these engines are clear of deposits. This is true even with the lowest octane autogas which is supplied in high altitude mountain states. None of the samples collected from this area were reported to have less than 80 Motor octane number. The lowest numbers are for unleaded grade. The average for samples of unleaded collected all over the

nation (winter 78-79 survey) was 84.3. The minimum Research octane number for unleaded was not less than 88 for any samples while the national average was 93.

On the other hand, it cannot be determined if the aviation Supercharge Rich mixture octane number requirements would be satisfied by any grade of autogas. This is because the Rich Aviation octane rating is measured in a test quite different from the Research method used for autogas. In an earlier section of this report some data correlating the Research octane rating method and the Rich Aviation method were discussed and no specific conclusions could be reached. Although it is probable that most, if not all, autogas meets the Rich Aviation requirement of 87 octane, standard correlating tests need to be run.

A subtle factor is the octane requirement increase with running (ORI). The fuel octane required to prevent knocking in an engine increases as the engine deposits form. Deposits build up from partial combustion products of both fuel and oil. Leaded fuels build up deposits in a different way than unleaded fuels. It is expected that autogas may cause more problems in this regard in that it has more heavy ends and a higher aromatic content than avgas. With leaded fuels the octane requirement usually builds up to some level then stays constant, while unleaded fuels cause a continually increasing octane requirement. Long term testing is needed, particularly with unleaded autogas, to determine if the increase in octane requirement is low enough so knock does not occur before the engine is overhauled and cleared of deposits. Perhaps a shorter overhaul period is necessary when autogas is used.

PREIGNITION AND DEPOSIT IGNITION. Preignition has been a greater problem in piston engine aircraft than it has in automobiles. The engine operating conditions most common with aircraft engines coincide with those which are most likely to result in preignition. These conditions are high speed, high output and high cylinder head surface temperature (14).

Preignition is the premature start of combustion. This occurs when normal flame propagation begins at a time before that programmed into the ignition system. This phenomena is distinctly different from knock which is the normal flame propagation followed by spontaneous combustion of part of the charge. Preignition can be caused by a hot spot somewhere in the combustion chamber. If the temperature of a part in the combustion chamber, such as a spark plug or a valve, becomes higher than the autoignition temperature of the fuel-air mixtures, it will ignite the mixture. If this occurs before the controlled electric spark, the ignition timing in effect will have been advanced. When combustion occurs too early the piston and combustion chamber are exposed to the hot combustion products longer and the work which the hot gases would have done on expansion is lost through heat transferred during compression. Such heat and pressure are particularly damaging to the piston which can fail catastrophically in a very short period of time, sometimes in as little as 30 seconds if the preignition is continuous. The damage is usually erosion of the piston ring lands or holes through the piston crown. A short burst of preignition will not lead to damage since some time is required to heat the

critical surfaces. In fact deposits may be burned off eliminating the preignition. Reports in the literature indicate that the temperature of the combustion chamber hot spots must be a minimum of 1600 to 1765°F (15), to cause continuous runaway preignition. When runaway preignition is occurring it is usually inaudible. This is because the ignition of the charge is so far advanced that the engine does not knock. Some backfiring through the intake may sometimes be heard, however.

Causes of runaway preignition include broken spark plug insulators, defective exhaust valve sealing and excessive spark knock. The spark plug is chosen with a heat range that will allow the tip of the spark plug to reach temperatures just under those that would cause preignition under the most severe operating conditions. This is to burn off deposits. If the heat flow path is disrupted in any way, such as a cracked insulator, leaking seal or loose spark plug, the temperature may increase high enough to cause preignition. If the exhaust valve starts to leak, the hot combustion gases blow past the valve head during the expansion stroke causing it to overheat. There are many things which can cause the exhaust valve to leak. The valve seat can warp so that it is not concentric with the valve head. The valve can stick due to deposits on the stem. Improper valve lash settings can cause the valve to slam into the seat with such force that it is damaged. Excessive spark knock can also cause preignition. The high rate of heat transfer caused by the scrubbing of the combustion gases can cause overheating of the combustion chamber parts, particularly the spark plugs and exhaust valves.

Knock may be brought on by fuel of too low an octane rating or it may be caused by deposit ignition. Some combustion chamber deposits can glow at a temperature high enough to ignite the mixture. This can cause preignition, but of a more stable type. Deposits can cause the ignition to occur before the time dictated by the ignition system, causing knock. The increased heat input from the knocking combustion to the walls causes the deposits to burn away at a faster rate, so the amount of unauthorized advance tends to be self-limiting. If the knocking, caused by the over-advanced timing causes other parts to be overheated, then runaway preignition can start.

From this discussion it is seen that the major impact of gasolines with regard to the problem of preignition is the character of the deposits formed by the fuel. Deposits are actually formed in the combustion chamber from two sources, the fuel and the oil including their additives, and these sources interact in two ways. One is the octane requirement increase effect. This is when the engine requires a higher octane fuel to prevent knocking as deposits in the combustion chamber build up. ORI is thought to be due in part to the compression ratio of the engine being increased by the volume taken up by the deposits, the heating of the charge by the thermal capacity and insulating properties of the deposits, and possible catalytic effects. Another way in which deposits affect preignition tendency is when the deposits themselves act as temporary hot spots which cause early ignition and associated knock.

One factor which has been found to be significant in the control of preignition

tendency of gasoline is its aromatic content. In general aromatic hydrocarbons (which are good antiknocks) are chemically more susceptible to preignition (15).

Not all aromatic compounds are poor for resisting preignition. Toluene is said to be good for avoiding hot spot ignition (17). Benzene and xylenes are poor for resisting both deposit and hot-spot surface ignition. Gasolines usually contain more toluene than any other aromatic. Very little benzene is included since this is a valuable chemical feedstock.

Most autogas contains a high percentage of aromatics. This is particularly true of unleaded grades. These aromatics (mostly toluene and some xylenes) are added to these fuels in place of lead antiknock compounds. Unleaded premium grades have the highest percentage of aromatics, sometimes exceeding 50% (18). Unleaded, regular and premium grades also tend to have high aromatic contents. Regular grade (autogas) is generally lower in aromatic content since lead antiknocks can still be used to good effect. Compared to avgas even regular autogas is considered relatively high in aromatics however. 100LL is the aviation grade with the highest aromaticity. In order to keep the lead content low, aromatics have been added. The amount of aromatics that can be blended into aviation gasoline is limited by the necessity of meeting the heating value specification. Aromatics have a lower heat content per pound than the other hydrocarbon components used and this has limited the amount of aromatics to an average of 10% and to a maximum less than about 25%. Most regular grade autogas has at least this much if not more.

Autogas often contains higher concentrations of olefins, which are also considered poor for preignition resistance (15). This is because olefins promote deterioration of gasoline and the aviation potential gum specification cannot be met if olefins are present in large quantities.

The market forces and government regulations are causing many changes in autogas composition. In the future the aromatic content may increase. Fuels derived from coal, shale or tar sands tend to be highly aromatic. Some autogas will contain MTBE (methyl tertiary-butyl ether) (19) or alcohols such as ethanol and methanol as octane extenders. Alcohols contribute to preignition problems while the effect of MTBE is not known.

Potential solutions to reduce the susceptibility to preignition problems may be a slight increase in spark retard and the addition of phosphorus compounds to the fuel. These compounds reduce glowing deposits and also reduce spark plug fouling. Since the phosphorus reacts with lead to form a complex lead phosphate (20), its use to prevent surface ignition with unleaded fuels would be questionable. More frequent engine teardown and deposit removal may be required with use of autogas.

To satisfactorily answer questions related to preignition tendency, long term tests similar to those suggested in the previous section under knock problems are required. In fact, since knock is often a precursor to preignition, the two problems are not entirely separable.

#### VOLATILITY RELATED EFFECTS.

VAPOR LOCK. Vapor lock is a partial or complete stoppage of fuel flow to an engine's carburetor caused by the formation of vapor in the fuel system. Its onset in an aircraft can be disastrous. Much of the following discussion is based upon references (21,37,40).

Vapor lock is probably the most serious problem to be overcome if autogas were to be used in place of avgas. Vapor lock is affected by the temperature and pressure of the gasoline in the fuel system, vapor forming characteristics of the gasoline, ability of the system to handle vapor, and the operating conditions of the engine. Vapor bubbles may occur anywhere in the fuel system, but the most critical point is usually the fuel pump. This is where the most heat transfer to the fuel will occur (with engine driven pumps) and the pump suction reduces the pressure which increases vapor formation. The specific volume of gasoline vapor at fuel system temperatures is about 160 times that of the liquid. Thus it can be seen that a pump of fixed maximum volume flow rate will not be able to deliver a high enough mass flow rate of fuel to the carburetor for full power if very much of the fuel has become vapor.

A parameter that is the ratio of vapor to liquid of a gasoline at a specific fuel temperature is called the V/L ratio. This is useful for predicting vapor locking tendency. V/L ratios can be measured in the laboratory with temperature—V/L equipment or approximately calculated using the ASTM D 439-X1.2 method from vapor pressure and distillation data (2). The Reid vapor pressure is a reasonably good predictor of vapor-locking tendency in aircraft. The Reid vapor test is performed at a V/L ratio of 4 and this is close to the V/L tolerance of many light aircraft. Figures 9 through 13 show calculated V/L curves plotted from the ASTM distillation data gathered from DOE fuel surveys for aviation and motor gasolines. The curves calculated from the procedures of ref. (2) show the amount of vapor formed as a function of fuel system temperatures and the variability from sample to sample. If the fuel temperature becomes higher than that temperature corresponding to the V/L tolerance of the aircraft, as indicated on the Temp-V/L curve, then vapor lock will begin to occur.

The V/L tolerance of most automobiles is between 15 and 25. Several surveys indicate that with some aircraft, V/L ratios less than 1 (17,22) can affect fuel pump operation and fuel metering with higher ratios causing stalling. When V/L ratios this low have such an influence on engine performance, then the release of dissolved air in the fuel becomes a significant factor. The amount of air which will dissolve in gasoline is small. It is usually not more than 20% by volume, but it is important from the standpoint of vapor lock because the air bubbles can carry large volumes of vapor as they are released (22). The dashed lines on Figures 9 through 13 show the dissolved air contribution to V/L. The amount of air that can dissolve in gasoline depends on the fuel vapor pressure. The sum of the partial pressures of the dissolved air and the fuel must equal atmospheric pressure (at equilibrium). Air is released with altitude and temperature increase.



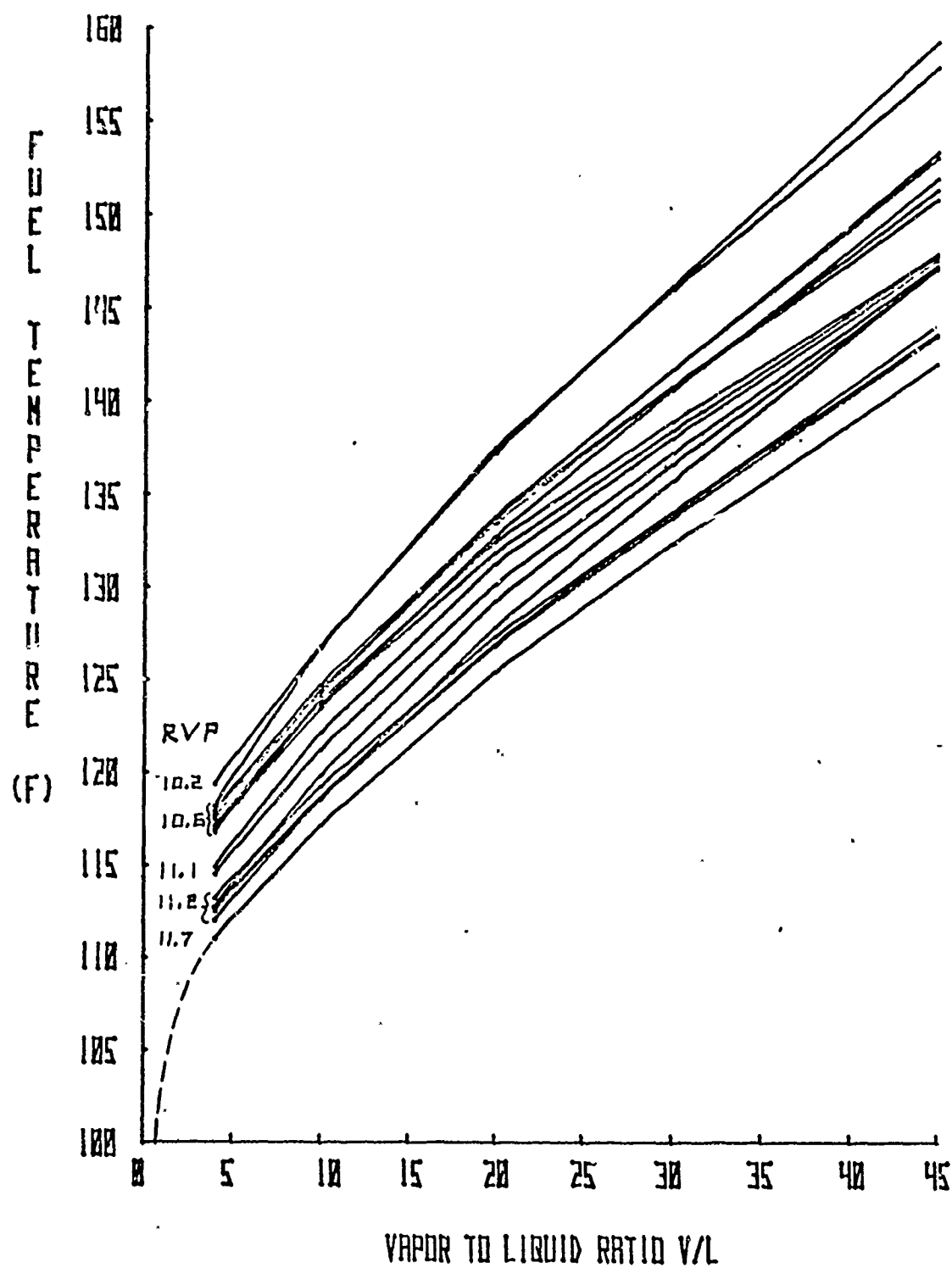


FIGURE 9. TEMPERATURE-V/L RELATION FOR SOME UNLEADED AUTOGAS SAMPLES AT SEA LEVEL PRESSURE (29.92 in.Hg) CALCULATED FROM ASTM DISTILLATION DATA REPORTED IN "D.O.E. MOTOR GASOLINES" SURVEY FOR DISTRICT 5 SUMMER 1979 (Ref. 12)

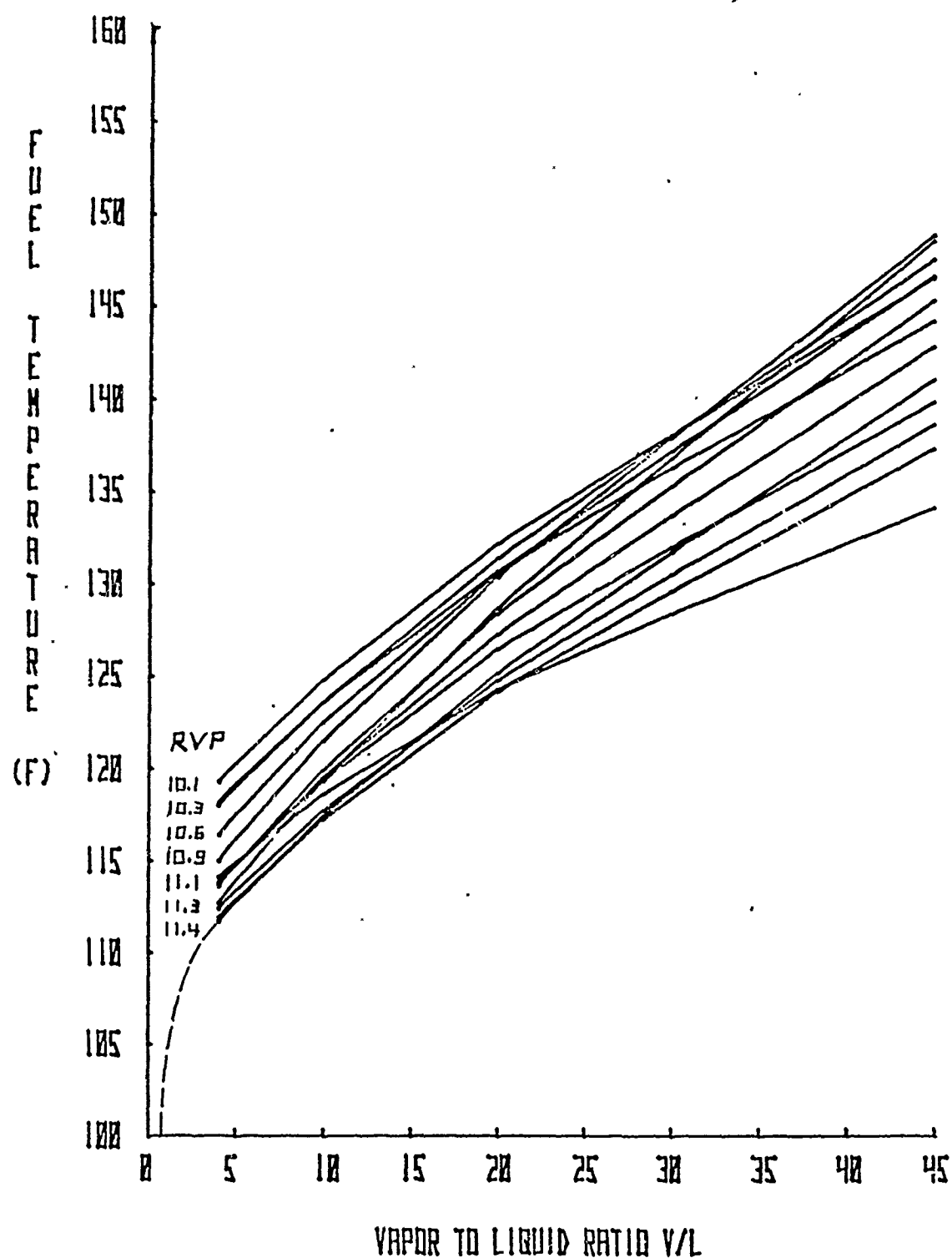


FIGURE 10. TEMPERATURE-V/L RELATION FOR SOME REGULAR AUTOGAS SAMPLES AT SEA LEVEL PRESSURE (29.92 in.Hg) CALCULATED FROM ASTM DISTILLATION DATA REPORTED IN "D.O.E. MOTOR GASOLINES" SURVEY FOR DISTRICT 5 SUMMER 1979 (Ref. 12)

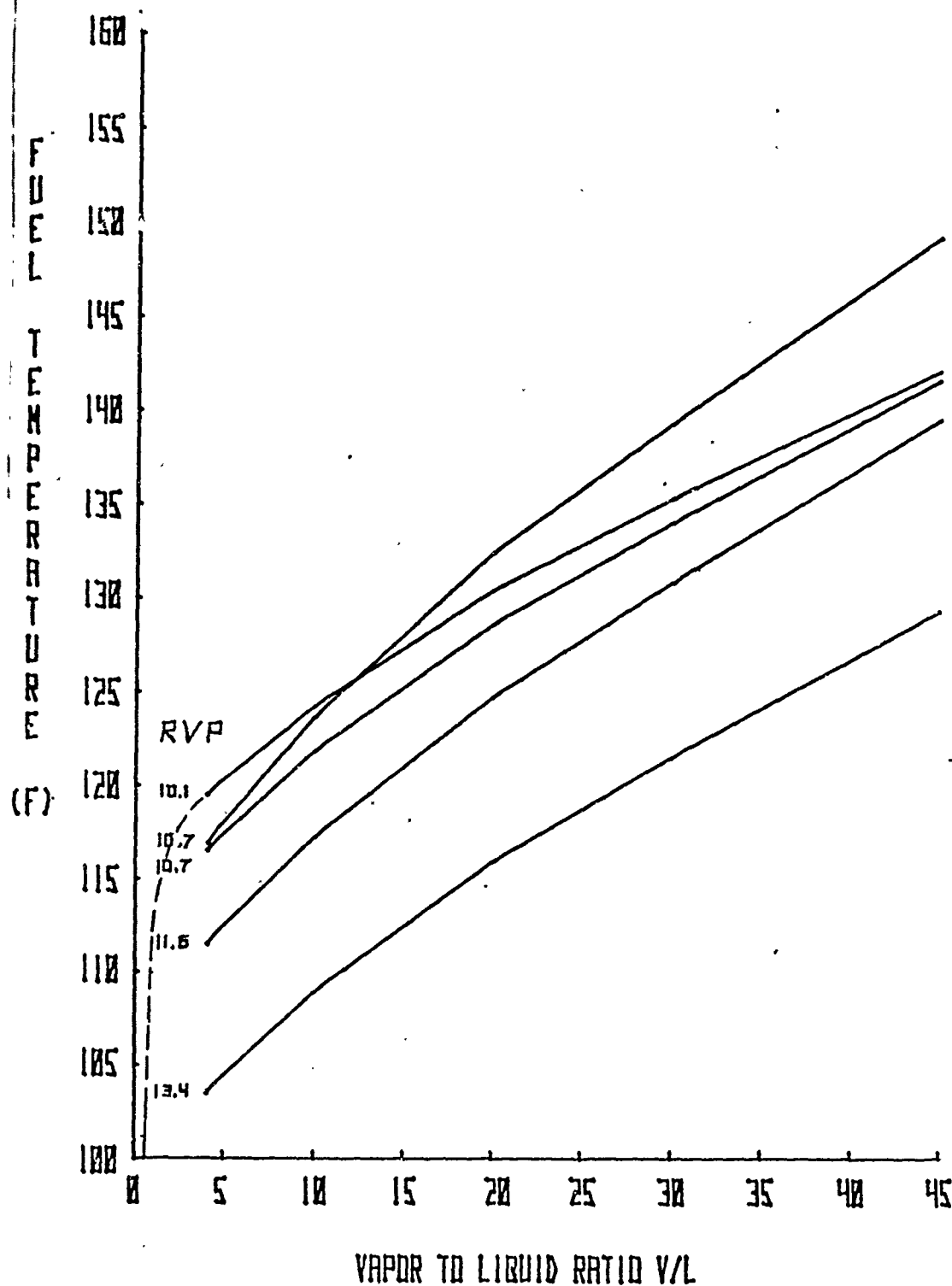


FIGURE 11. TEMPERATURE-V/L RELATION FOR SOME PREMIUM AUTOGAS SAMPLES AT SEA LEVEL PRESSURE (29.92 in.Hg) CALCULATED FROM ASTM DISTILLATION DATA REPORTED IN THE "D.O.E. MOTOR GASOLINES" SURVEY FOR DISTRICT 5 SUMMER 1979 (Ref. 12)

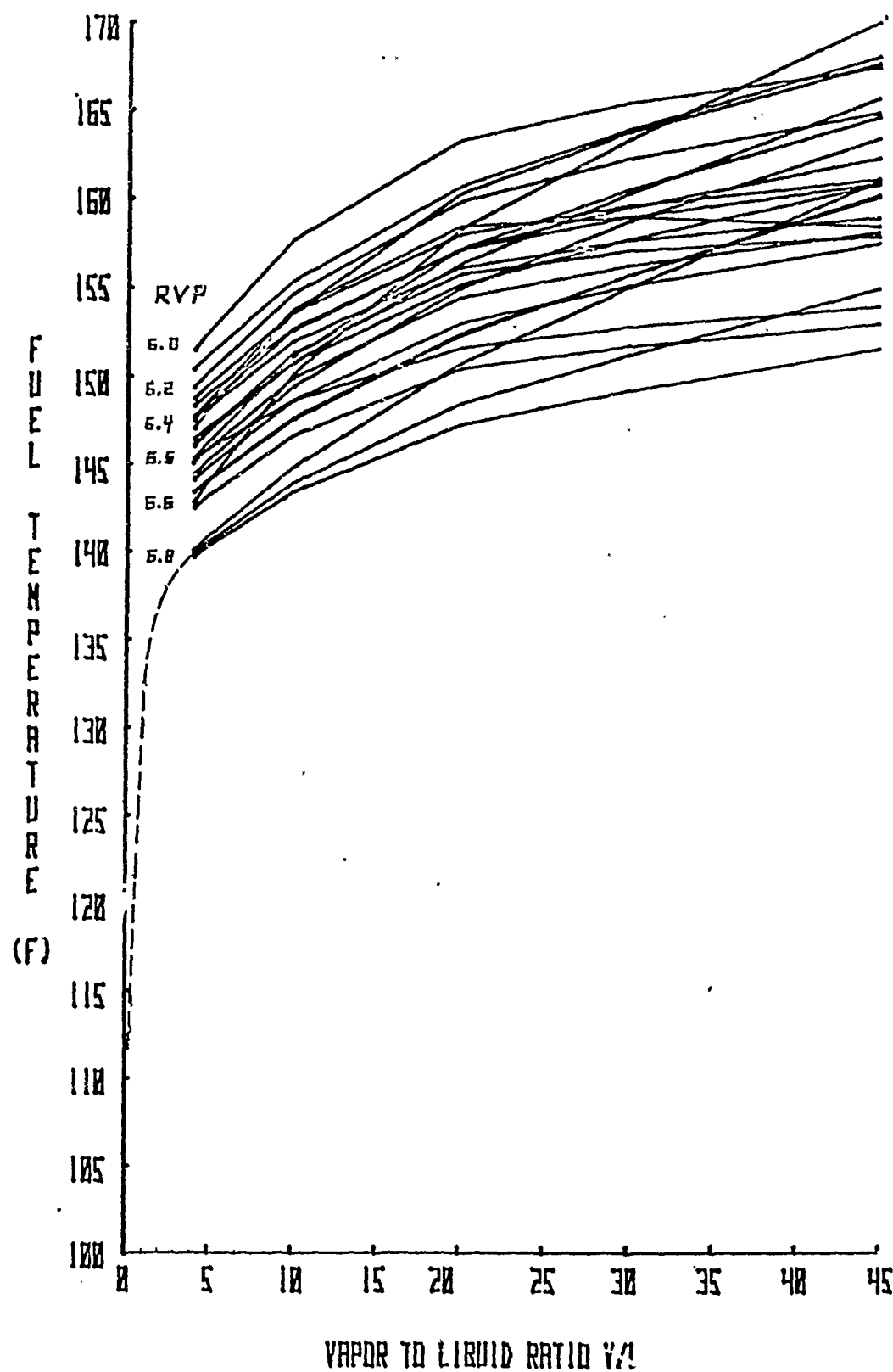


FIGURE 12. TEMPERATURE-V/L RELATION FOR SOME AVIATION GRADE 80/87 SAMPLES AT SEA LEVEL PRESSURE (29.92 in.Hg) CALCULATED FROM ASTM DISTILLATION DATA REPORTED IN THE 1969 BUREAU OF MINES-API SURVEY (Ref. 13)

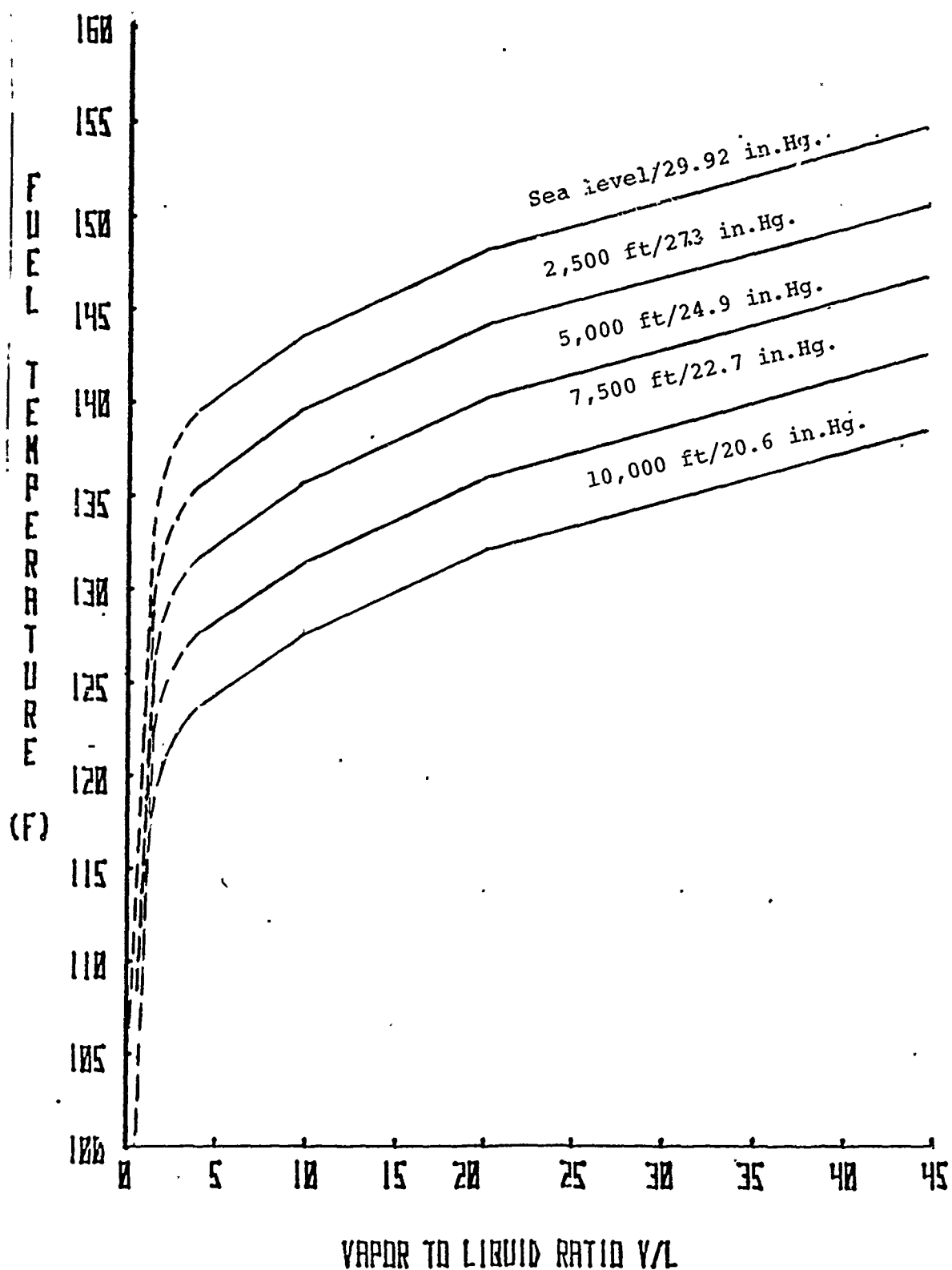


FIGURE 13. EFFECT OF ALTITUDE/PRESSURE ON THE TEMPERATURE-V/L RELATION OF ONE SAMPLE OF 80/87 GRADE AVGAS

Figure 13 shows the effect altitude (decreasing pressure) has on the temperature-V/L relationship. This indicates that an aircraft with a given V/L tolerance would vapor lock at 10,000 ft with a fuel temperature 16°F lower than it would at sea level, all other factors being equal. Figure 14 shows that rate at which atmospheric temperature drops with altitude. This shows that a 10,000 ft gain in altitude decreases the ambient temperature an average of 35°F. If the fuel tank temperature could come to equilibrium with the ambient temperature more rapidly then the two effects would tend to cancel and vapor lock tendency would not increase with altitude. In general fuel temperature lags the ambient with a tendency to aggravate vapor lock characteristics during an ascent. Consideration might be given to a low pressure drop fuel to air heat exchanger cooled with unheated ambient air. The object would be to rapidly cool the fuel to the ambient.

In considering the use of autogas in an aircraft, it is important to know the V/L tolerance of the aircraft. This is the ratio above which the engine leans out and has an unacceptable reduction in power. The way to determine this is to measure pressure and temperature at the location along the fuel system where vapor lock is expected. Then if the V/L vs. temperature data are available for the fuel, the limiting V/L ratio can be found. Having measured the temperature rise above ambient for different operating conditions, the limiting fuel volatility that may be used without encountering vapor lock can be predicted. Operating conditions affecting vapor lock tendency are initial fuel temperature, ambient temperature, altitude and rate of climb. If the V/L ratio tolerance measured for a particular aircraft is very low, much less than 20, fuel system modifications would be of help. The modifications might include increasing the fuel pump capacity by the addition of a larger capacity fuel pump, or the reduction of heat transfer to the critical fuel system parts. One potential modification to consider would be the elimination of the engine-driven diaphragm pumps completely. Placing centrifugal fuel pumps in the tank reduces the temperature rise of the fuel while pressurizing the fuel system. By pressurizing the fuel system along its entire length, the danger of air introduction into the suction piping is also eliminated.

Some studies of automotive fuel systems indicate that a "bottleneck point" usually occurs at the fuel pump inlet. Most carburetors can handle V/L ratios upwards of 45, but with some loss of fuel economy due to excessive richening. The low pressure fuel injection systems as used on some aircraft are relatively intolerant of vapor and are likely to be the bottleneck point. The fuel tends to pick up heat at the engine-driven fuel pump because of the pump's large surface area and the relatively low fuel velocity through it. The pressure is reduced at the inlet check valve which increases vapor formation. Fuel not used by the engine is bypassed in the pump back to the inlet which further increases the temperature of the fuel. To solve automotive vapor locking problems, pumps have been sized to handle V/L ratios of 15 to 25, and mounted upstream of the engine to minimize heat pick up. Current aircraft fuel pumps have not been designed to handle V/L ratios much above 4 because the V/L curve for avgas starts to become flat at this point as Figure 12 shows and thus if fuel temperatures exceed this point very large V/L ratios are readily generated. This design was recommended in a paper by the CFR

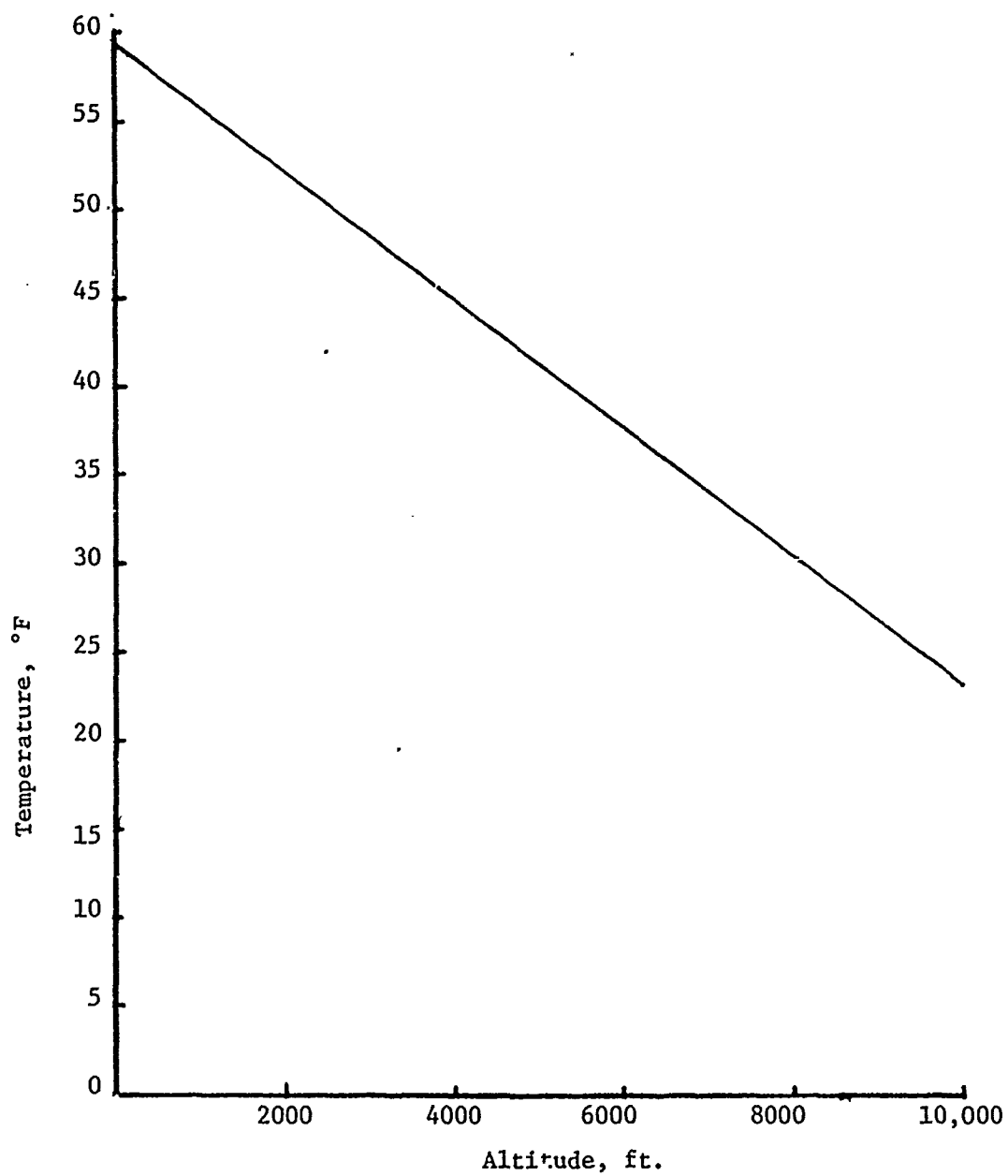


FIGURE 14. REDUCTION OF ATMOSPHERIC TEMPERATURE WITH ALTITUDE (DATA FROM NACA STANDARD ATMOSPHERE TABLE)

Aviation Fuels Division (37) since large increases in pumping capacity allow very little gain in vapor lock safety margin. The V/L curves for autogas, Figures 9 through 11, do not level off like those for avgas so increasing pump capacity is more effective. Other solutions used in automotive fuel system design practice include careful routing of fuel lines away from heat sources and vapor separators/return lines in troublesome applications.

It should be kept in mind that fairly small differences in the ASTM 10, 20 and 50% distillation points can have significant effects on the V/L vs. temperature curve. Particularly the steepness of the curve is important. If the curve is nearly level the difference in critical fuel system temperature between a V/L ratio which begins to cause leaning and the V/L ratio which causes stopping of the engine is very small. This means that there is even less warning time to recognize the symptoms of vapor lock.

Tests to examine the impact of autogas on light aircraft fuel systems are needed. Mock-up fuel systems can be set up in the laboratory and subjected to a variety of temperature and pressure or vacuum conditions. Some aircraft may be "fixed" by the addition of suitable intake pumps. Prototype systems need to be developed and evaluated. Solutions appear possible but aircraft fuel system modifications may be required, especially in sensitive aircraft such as low-wing models.

#### ICING.

Carburetor icing can result in engine malfunction or power reduction, and arises from ice formation in the carburetor (23). It has been observed that this is due to the restriction of air flow past the throttle plate caused by formation of ice on the throttle plate and interior of the carburetor barrel; particularly during light-load operation. Under higher load conditions, ice is most likely to form in the venturi area, choking the air flow and enriching the mixture. The atmospheric conditions most likely to cause carburetor icing are ambient temperatures of 25 to 60°F and 100% relative humidity (see Figure 15). The cooling of the air caused by the throttling and evaporation of the fuel causes atmospheric water to condense out while making the throttle plate cold enough for this moisture to freeze. Fuel volatility significantly affects the tendency for carburetor ice formation in some engines depending upon relative humidity (see Figure 16). The parts of the fuel boiling range which seem to affect icing tendency the most are the 10% and 50% evaporated ASTM distillation points (23). The higher the volatility, or the lower the percent evaporated temperature, the more likely carburetor icing is to occur.

The 10% and 50% points of 80/87 avgas as reported in the 1969 fuels survey are 146±6, and 198±18°F, respectively. The winter 78-79 Motor Gasoline survey shows the national average 10% point for winter gasolines are unleaded 106±5°F, regular 106±7, premium 107±6. (The ± temperature indicated is the average variation in each district.) The 10% point for summer gasolines were all higher at 120°F. The 50% points for winter autogas are unleaded 215°F, regular 202, premium 209, all





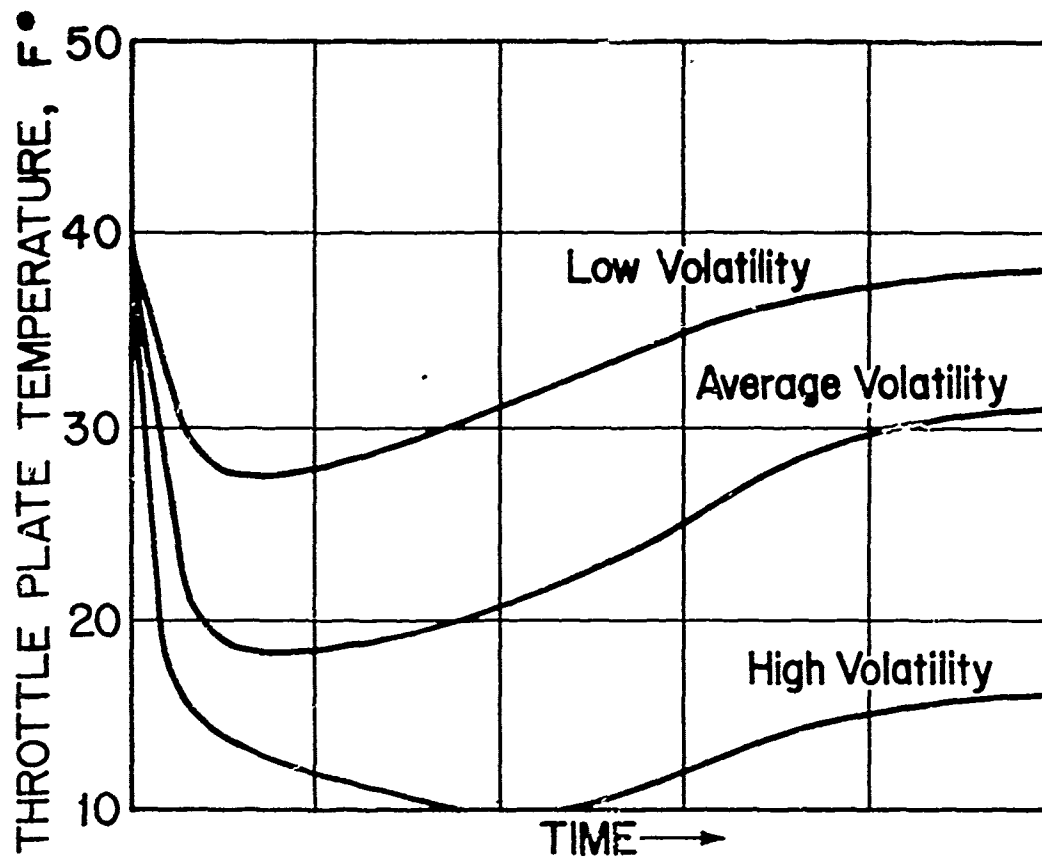


FIGURE 16. EFFECT OF FUEL VOLATILITY ON THROTTLE-BLADE TEMPERATURE  
At 40° F ambient temperature. (Figure from Reference 23)

$\pm 15^{\circ}\text{F}$ . Summer autogas 50% points are about  $6^{\circ}\text{F}$  higher.

This information indicates that the front half (that between the initial boiling and 50% points) of autogas is more volatile than avgas. Figure 3 indicates this, and also the variation likely to be encountered, graphically. This front half is the portion of the fuel which evaporates in the carburetor area of the intake tract. As the throttle is opened, less of the fuel is evaporated at the carburetor. Also, as the airflow increases, the pressure drop due to throttling of the air increases. The fuel added to the airstream at the venturi acts as a liquid refrigerant. As the vapor pressure of a refrigerant increases, the temperature at which it can evaporate and provide cooling decreases. Since the front end of autogas has a higher vapor pressure than avgas, increased carburetor icing problems will be likely.

One way to estimate the potential for carburetor icing with a given fuel and an engine which is sensitive to icing is a carburetor icing index which some fuel system engineers use. This index is the sum of the 10 and 50% point temperatures plus one-fifth of the 90% point temperature. The higher the index, the less likely the fuel is to cause icing because larger numbers arise from fuels of low volatility. This index was developed for idle type icing in automotive engines.

Using distillation data from the fuel surveys, some calculations were made as follows. For 80/87 avgas the average carburetor icing index is 391. The lowest was 369. For autogas some numbers are:

	Average	Lowest
	Sample	Sample
Winter unleaded =	387	347
Summer unleaded =	410	361
Winter regular =	376	350
Summer regular =	398	363
Winter premium =	382	350
Summer premium =	402	354

Indexes below 390 are considered borderline without antiicing additives. The average index numbers indicate that the more volatile winter autogas probably will cause slightly greater carburetor icing problems while summer gas would be slightly better than avgas in this regard. Individual samples of autogas can be much worse in terms of carburetor ice because of the extreme variability of autogas.

Some autogas may contain additives to reduce carburetor icing, either freezing point depressants or surface active agents. The ASTM specifications for autogas allow these but do not require them. Since most automobiles now have automatic intake air heaters, the need for antiicers has diminished.

Another icing phenomena is fuel filter icing. This occurs when water which is dissolved in the fuel becomes insoluble and freezes into fine ice crystals which can

rapidly clog a fuel filter. Autogas has a larger proportion of aromatic hydrocarbon compounds than does 80/87 avgas. Aromatic compounds can hold more water in solution than other hydrocarbon types. If on cooling, the water is thrown out of solution and phase separation occurs, there is danger that slugs of this water can get into the fuel lines and freeze, blocking the flow.

A potential solution to carburetor icing and fuel system icing might be the addition of an approved antiicing compound at the time of refueling. Ethylene glycol monomethyl ether at 0.10-0.15% by volume is said to be particularly effective (24). Also, it has been reported that the installation of a teflon-coated throttle plate can be effective in preventing ice adhesion to the throttle plate (24). More information is required on possible solutions to the icing problem.

COLD START AND WARM UP. The best indicators of the starting characteristics of a fuel are its Reid vapor pressure and the ASTM distillation test 10% point. A high Reid vapor pressure and low 10% temperature indicate a more volatile fuel.

According to the fuel survey data, 80/87 avgas on the average had a Reid vapor pressure of 6.5 (nationwide average) compared to the annual average range of 9.5 to 12.5 for autogas. The ASTM 10% point of 80/87 is very high at 146°F compared to the range of 105 to 120°F for autogas (the lower value is found in winter gas). With autogas fuels of such high volatility, the starting routine would have to be modified somewhat to avoid creating a mixture which is too rich to permit the engine to start. In general, however, improved cold starting would be expected with more volatile fuels such as autogas. The reason that avgas is made with such low volatility is because the vapor pressure and 10% point have such pronounced effects on the more serious problems of carburetor icing and vapor lock.

The ASTM 50% point indicates the ability of the gasoline to supply a proper mixture during the warm-up period particularly during sudden throttle openings. The 50% point also critically affects carburetor icing which is likely to occur during warm up. 80/87 avgas has a 50% point of 198°F compared to the 200-220 range for autogas. This would indicate that the avgas should have a slightly better warm up and response to throttle opening than autogas. Because the front end volatility of autogas is so high, the carburetor icing tendency of autogas is greater than avgas as discussed in the previous section. This can adversely affect warm up performance.

MALDISTRIBUTION. The ASTM 90% point indicates the amount of high boiling components in a gasoline. The amount of these boiling components determines how good the mixture distribution will be, particularly in an unheated intake manifold. Poor distribution causes rough running, resulting in more stress in propeller and crank. It can also lead to knocking in one or more cylinders, piston damage and spark plug fouling. Maldistribution is also associated with worsened fuel economy. Too much high boiling point components can cause liquid fuel to wash oil off the cylinder walls and dilute engine oil. If the boiling point of this liquid is much higher than the normal maximum oil temperature then it stays with the oil until it is changed. There is a large difference between the 90% point of avgas and autogas.

Based on the 1969 survey (13) the average 90% point of grade 80/87 was 236°F compared to a range of 330 to 340°F for automotive gasolines (11,12). In automotive engines these high boiling components are tolerated because the engine designer was willing to trade off some maximum power (through loss of volumetric efficiency) by heating the intake manifold and heating the intake air. Also, the piston to cylinder clearances are very small so relatively little liquid fuel can blow by into the crankcase oil.

The temperature at which the last of the liquid fuel evaporates in the ASTM distillation test is called the end point. Like the 90% point, it also indicates the presence of heavy ends. If the difference between the 90% point and the end point is greater than about 70 to 80°F there may be a cleanliness problem depending on the hydrocarbons making up these heavy ends (25). The average end point of 80/87 is only 294°F, 58°F above the 90% point. For automotive fuel it is 410 to 430°F, about 80°F above the 90% point. Autogas may have a variety of detergent additives to control engine cleanliness, particularly in the carburetor and intake system. These are usually surface active agents present in very small quantities. The heavy ends in autogas cause carbon deposits to build up on the intake valve tulips. This can disrupt air flow, increase maldistribution and decrease maximum power available. Those aircraft engines which have the intake system mounted below the engine and/or are heated externally would have less problems with maldistribution.

The extent to which the greater maldistribution expected with autogas will adversely affect the aircraft engine performance needs some study. Long-term tests are required to study deposit formation and crankcase dilution. Cylinder-to-cylinder fuel distribution measurements under various engine operating conditions and attitudes are needed to quantify the increased maldistribution problem.

#### SPARK PLUG FOULING.

The nature of deposits on a spark plug depends on the plug insulator tip temperature, time of exposure, fuel/air ratio, tetraethyllead content of the fuel, scavenger used in the fuel, and contaminants in the atmosphere. Low temperature deposits which accumulate on the spark plug commonly are electrically conductive. These deposits therefore provide an electrical contact from the spark plug center electrode to a ground (the cylinder head).

Spark plug fouling arises from two main sources, the fuel and the oil. Oil consumption in an aircraft engine is high, as compared to an automotive engine. Of the oil which enters the combustion chamber, some may not burn and may accumulate on the spark plugs, especially on the lower plug. Oil fouling of spark plugs is thought to be independent of fuel type.

Another major cause of spark plug fouling is associated with the higher boiling compounds in the gasoline. Some of these fail to burn completely and accumulate on the spark plugs, especially on the lower plug. Figure 1 shows that the 80 to 100% evaporation region of the distillation curve is indicative of spark plug

Based on the 1969 survey (13) the average 90% point of grade 80/87 was 236°F compared to a range of 330 to 340°F for automotive gasolines (11,12). In automotive engines these high boiling components are tolerated because the engine designer was willing to trade off some maximum power (through loss of volumetric efficiency) by heating the intake manifold and heating the intake air. Also, the piston to cylinder clearances are very small so relatively little liquid fuel can blow by into the crankcase oil.

The temperature at which the last of the liquid fuel evaporates in the ASTM distillation test is called the end point. Like the 90% point, it also indicates the presence of heavy ends. If the difference between the 90% point and the end point is greater than about 70 to 80°F there may be a cleanliness problem depending on the hydrocarbons making up these heavy ends (25). The average end point of 80/87 is only 294°F, 58°F above the 90% point. For automotive fuel it is 410 to 430°F, about 80°F above the 90% point. Autogas may have a variety of detergent additives to control engine cleanliness, particularly in the carburetor and intake system. These are usually surface active agents present in very small quantities. The heavy ends in autogas cause carbon deposits to build up on the intake valve tulips. This can disrupt air flow, increase maldistribution and decrease maximum power available. Those aircraft engines which have the intake system mounted below the engine and/or are heated externally would have less problems with maldistribution.

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fouling. Figure 3 shows that autogas has a much higher 90% distillation temperature and therefore a larger volume of heavy ends compared to avgas. Thus autogas can be expected to increase plug fouling problems.

A further complication in using autogas in aircraft which affects spark plug fouling is that of maldistribution. This was covered in a previous section in this report. As noted there, these small aircraft engines are subject to maldistribution due to the design of their intake manifolds and due to various attitudes which they may experience. Given maldistribution, use of autogas would result in more of the high boiling compounds of the fuel entering the rich cylinders and this would amplify fouling tendencies in those cylinders.

Lead in the fuel also contributes to deposits on spark plugs, and is well known to be the major cause of plug fouling. In 1974, the FAA Aviation News (36) reported experimental data which shows how spark plug fouling increases with increased lead content of the fuel. Their curve is reproduced as Figure 17.

Figure 7 shows actual lead content of avgas and autogas surveyed across the United States. This figure shows the average lead content of 80/87 avgas to be about 0.3 ml/gal, whereas the average lead content of autogas is shown to vary between about 1.7 ml/gal for winter regular and about 2.2 ml/gal for summer premium. Note that the lead content of unleaded autogas is so low that it is not even rated. Comparing the above with the results in Figure 17, it is obvious that using regular or premium autogas in an aircraft engine designed for 80/87 avgas probably will result in more spark plug fouling.

Another example which illustrates lead fouling is the lengthening of recommended spark plug change intervals by the automotive industry. A short while ago a typical spark plug change interval suggested by the manufacturer was around 12,000 miles. Today with use of lead-free gasolines a typical spark plug change interval is about 22,500 miles or nearly twice that with the leaded fuels.

It is well to point out that using unleaded autogas exclusively in an aircraft engine designed for 80/87 avgas may result in valve seat recession. To the extent that such valve problems may arise, a mixture of unleaded and leaded grades may alleviate the problems. However standard tests will be required to determine the extent of any problems and the effectiveness of solutions.

#### HOT RESTART.

Hot restart is a problem of starting a previously run hot engine. Deposit ignition and vapor lock are two key factors which contribute to the inability to re-start a hot engine. Two situations can be distinguished, hot restart on the ground and in the air.

When on the ground and the engine has been off for a short period of time, it may be difficult to restart. One cause is heat transferred from the engine to the fuel

system. With no fuel or air flow to cool the fuel system, enough vapor is formed to cause vapor lock. Another cause is preignition. Preignition causes high compression pressures and slow cranking. In an extreme case the engine may fail to rotate.

The severity of the hot restart problem depends on the nature of combustion chamber deposits and the temperature of the parts. These problems will be more likely to occur with automotive gasolines because of their higher volatility, greater deposit forming tendency and higher aromatic content. Automotive starters are chosen on the basis of maximum torque needed to crank a hot engine with deposit ignition. This can be greater than that required to crank a cold engine. High power starters and batteries are too heavy for light aircraft and thus hot restart will be more difficult with autogas. In general this is not a safety problem.

In flight, a hot restart problem is less likely to occur. This is because there is some cooling air available to minimize heat buildup and thus vapor formation is reduced. Moreover the windmilling forces on the propeller help provide the power to overcome the kicking back of the engine encountering preignition. Nevertheless any greater hot restart problem arising from use of autogas poses an increased safety problem for the aircraft.

#### FUEL SAFETY.

Toxicity and fire hazard are fuel safety problems. Key factors affecting the fire risk of a fuel are its flash point, spontaneous ignition temperature, flammability limits and the temperature range over which a combustible mixture will be formed over the liquid in a closed tank. This flash point is defined as the lowest temperature of the sample corrected to a pressure of 760 mm Hg at which application of an ignition source causes the vapor of the sample to ignite under specified conditions of test (ASTM D 56). The flash point of avgas is about -40°F (27). Automotive gas has a flash point somewhat lower because of its higher volatility and vapor pressure. The flash point is useful for predicting the fire hazard caused by spillage during refueling operations or at an accident site. It seems that both avgas and autogas are extremely dangerous in this regard.

The self-ignition temperature (SIT) of a fuel represents the minimum temperature above which it will burst into flames without the aid of a source of ignition and relates to fires arising from fuel spills on hot surfaces. The SIT of avgas is about 1329°F (22). In the case of a fuel line leak in the engine compartment, fuel spilled on a hot exhaust manifold may burst into flames (22) although such occurrences are rare. The high boiling point fuel components tend to have lower self-ignition temperatures than the more volatile components. If fuel splashes on the hot manifold and the more volatile components vaporize, the remaining heavy ends may self-ignite. In theory since autogas contains a larger volume of high boiling point constituents, its fire potential is at least as great if not greater than avgas.



Another factor to consider is under what conditions will the vapor mixture above the fuel in the fuel tank be flammable. When the mixture is richer than the lean limit of flammability (26 to 30 to 1 air-fuel ratio) a sufficient source of ignition will cause this mixture to ignite. The air-fuel ratio of the vapor space depends on tank temperature, pressure and fuel volatility. For avgas at ground level, the flammable tank temperatures are about 14°F for the rich limit to -40°F for lean limit. These temperatures decrease with altitude becoming 0°F to -54°F at 10,000 ft (22). Since autogas is more volatile than avgas, lower temperatures are required to produce combustible tank vapor mixtures. Therefore autogas may be slightly safer with regard to fuel tank explosions although such explosions are not common.

In general skin contact with autogas may be slightly more hazardous than avgas because of its higher volume of aromatic compounds of which some are known carcinogens. Further, exhaust emissions from autogas may be slightly more toxic to breathe due to their greater aromatic content as well.

In conclusion there appears to be only very minor differences between the fire hazard or toxicity of avgas and autogas. They are both about equally safe or unsafe depending on one's point of view.

#### ENGINE DURABILITY.

EXHAUST VALVE LIFE. Much development work has been done and much has been published on the effects of fuels and oils on exhaust valve life, in particular lead antiknock concentration. Problems attributed to lead antiknocks in gasoline have generally been solved. In most cases, the solution has been a matter of design, metallurgy operating conditions, overheating and in some cases, the fuels and lubricants. An example is the carbonaceous deposit accumulation in the thin annular space between the valve stem and guide. This accumulation can cause sticking and eventually valve burning.

Another of the common causes of exhaust valve sticking arises from cylinder head temperatures which are periodically too low. Many small aircraft do not have cowl flaps that are adjustable, hence under idling or low output approaches for a landing, temperatures in the exhaust valve guide area can be quite cool. Cool temperatures cause deposits from unburned fuel and oil to accumulate between the valve stem and the guide and subsequently during high output operation these deposits will form hard coke and interfere with valve rotation. In the absence of rotation, the valves will soon burn, crack, or otherwise fail. Because autogas with its higher volume of high boiling point constituents is expected to accelerate deterioration of the crankcase oil, the above potential lubrication problem is exaggerated. This phenomena is well documented in the automotive literature.

VALVE SEAT RECESSION. Valve seat recession is a phenomenon that can be described as the valve head walking down into the valve seat. It is also called "valve seat wear" or "valve seat pickup." This phenomenon occurs only with unleaded gasoline,

and can be quite severe under high temperature, high output conditions. The problem can occur with air-cooled or liquid-cooled engines. It became well understood years ago and has in general been solved with proper metallurgy of the valve seat. Prior to the development of adequate seat metallurgy, small air-cooled aircraft engines were operated on a run-in schedule using leaded gasoline before being released for subsequent operation on unleaded gasoline. The seat recession problem was reduced considerably because the lead deposits on the seats provided protection.

There have been cases where small engines designed for low lead or no lead subsequently became distressed when higher lead concentrations were used. Minor changes in design or changes in metallurgy usually took care of the problem. It is not known whether any valve recession problems would arise with the use of lead free autogas.

It has been found that the heavy ends or the high boiling portions of gasolines makes the greatest contribution to deposits in the engine. This generally applies to combustion chamber deposits, exhaust valve deposits and deposits on valve stems. A wide range of additives is used in motor gasolines and oils to handle these deposits and their effects.

Aviation oils do not contain the large complement of additives that are used in motor oils. Only non-metallic antioxidants and polymeric dispersants are used. Metallic dispersants and detergents used in motor oils could cause preignition in the aircraft engine. In order to provide adequate lubricity and load-carrying capacity, aviation oils contain components which tend to cause slightly more deposits. Except for deposit problems mentioned above, the effects of these deposits are small.

Use of autogas in aircraft with their higher blowby rate is expected to deteriorate the aviation oil rapidly with resulting problems of crankcase sludge and varnish. Automotive oils are proven in ASTM Sequence tests which to a significant extent are designed to exacerbate autogas induced problems. For that reason aviation oil would be totally inadequate in a modern automobile engine. Standard tests need to be developed which can correlate exhaust valve deposits and sticking to the heavy ends of the fuel.

ENGINE WEAR. A search of the literature shows a paucity of engine wear data and engine wear reporting. This is probably due to the fact that an engine has to qualify adequately before it is certified for aircraft use. Implied in the certification is acceptable wear and freedom from problems associated with high wear.

There occasionally are situations wherein because of the habits of the operator, cylinder bore rusting will arise. This situation can arise if the engine is allowed to idle or taxi for long periods of time with the carburetor fairly rich and the engine quite cool. If the engine is shut down at the ignition switch rather than by turning the fuel off, and is then allowed to remain idle for long periods of time without turning over, barrel rusting can and does occur. This can be

aggravated somewhat during fairly long approaches at constant low throttle opening. The engine tends to operate rich and liquid fuel tends to get on the cylinder walls, washing away a part or most of the protective lubricating oil. It is a combination of the rich mixture washing oil off the walls and low temperature that sets the stage for eventual cylinder bore rusting. The greater aromatic and sulfur content of autogas and the generally higher chlorine and bromine content (higher lead level) may intensify this problem.

In the past, engine failures have occurred due to some deficiency in the oil or fuel. Fuel-related failures such as those caused by detonation and preignition have been covered elsewhere. These failures resolve themselves in broken, burned, or seized pistons, burned valves, broken spark plug insulators, and broken or stuck piston rings.

There appears to be relatively few problems in the cam and tappet area of the small air-cooled, aircraft engine. Developments in design and metallurgy (compatibility) are responsible for the advances in this area. Generally the cam tappet area will have the highest momentary pressure in the engine. This occurs at the start of the lift of the valves. It is particularly true with the exhaust valve where it is desirable to pop off the seat quickly so as to drop the pressure in the combustion chamber and reduce the velocity of the gases exiting the combustion chamber past the valve and seat thus reducing heat transfer to the valve and seat.

In summary, use of autogas is expected to accelerate oil degradation and the higher sulfur content will increase engine corrosion. Standard durability tests need to be run with fuels having a large volume of heavy ends and a "high" sulfur content in order to establish any necessary change in overhaul or oil change interval. Possible solutions are an increase in oil detergency and a bypass type full flow oil filter.

#### COMPATIBILITY WITH MATERIALS AND CORROSION.

NON-METALLIC MATERIALS. Problems with the polymeric materials in the fuel systems of both aircraft and automobiles have been reported recently. The problems in aircraft systems have been associated with those regions where the newly introduced 100LL was particularly high in aromatics (20% or more). The following table from Reference (26) reports some malfunctions and their causes experienced by new or nearly new light aircraft shortly after the introduction of this fuel.

The potential problems of non-metallic materials in contact with fuels are difficult to quantify. Non-metallic materials are generally organic and include plastics, elastomers and cork or leather for some gaskets. These materials consist of blends of high molecular weight polymers or molecular networks and may contain low molecular weight additives to protect the polymers from ultraviolet radiation, heat and chemical degradation and to reduce cost. Non-metallic materials in contact with fuel are subject to three effects. They are volume change, changes in physical properties and chemical attack. Volume change occurs when fuel is absorbed causing

Malfunctions and their causes experienced in light aircraft after introduction of 100LL Avgas (Ref. 26).

<u>Part</u>	<u>Problem</u>	<u>Cause</u>
Fuel Selector Valves-- Spool type	Hard to turn, leaked internally when dried out-loss of function	Swelling of "o" ring seals Material migration or excessive shrinkage
Shear plate type	Internal leakage, external leakage at shear plate shaft seal	Swelling of sealing "o" rings Shaft seal swelling
Ball and cam type	External discharge at shaft seal	Excessive swelling of shaft seals
Electric Fuel Pumps	Leakage of fuel at pump shaft lip seals	Swelling of seal increases diameter of lip
Fuel Flow Detection Switches	False indications lock-up of elements	Swelling of "o" rings
Gaskets--Fuel Filler Adaptors and Inspection Covers	Leaks	Excessive shrinkage when exposed to dry-out
Fuel Flowmeter	Metering rotors locked	Swelling of plastic bearings
Submerged Electrical Connectors	Swelling and cracking of potting compounds	
Tank Vent Lines, Bladder Assemblies and Fuel Hose	Deterioration	
*Float Bowl Carburetor Gasket	Loss of sealing and engine mixture leaning	Shrinkage

\*Data from Reference (18).

swelling or when low molecular weight materials are leached out leading to shrinkage. In those applications where dimensional stability is important excessive swelling or shrinkage can cause binding or leakage. Changes in physical properties usually accompany changes in volume. As the volume increases, the tensile strength, modulus, hardness and tear resistance decrease. Chemical attack may cause large changes in properties independent of the changes caused by fuel absorption.

The volume increase of a polymeric material is a function of the nature of the material and of the fluid medium. The basic property defining swell behavior is known as the solubility parameter. This is composed of three interaction modes consisting of dispersion ( $\delta_D$ ), dipole ( $\delta_P$ ) and hydrogen-bonding ( $\delta_H$ ). These are known as partial parameters. The overall solubility parameter ( $\delta$ ) is defined as the square root of the cohesive energy density:

$$\delta = \left[ \frac{\Delta E}{V} \right]^{1/2} = \left[ \frac{\Delta H - RT}{mw/d} \right]^{1/2} = \left[ \delta_D^2 + \delta_P^2 + \delta_H^2 \right]^{1/2}$$

where:  $\Delta E$  = energy of vaporization

$V$  = molar volume, molecular weight ( $mw$ )/density ( $d$ )

$\Delta H$  = heat of vaporization

$R$  = gas constant, 1.978 cal/(deg)(mole)

$T$  = absolute temperature

The units of these parameters are (calories/cm<sup>3</sup>)<sup>1/2</sup> (called Hildebrand units).

The overall solubility parameter is the vector sum of the three interaction modes. The overall parameter ( $\delta$ ) and partial parameters ( $\delta_D, \delta_P, \delta_H$ ) for some liquids and polymer materials are listed in Table 4.

When the partial solubility parameters of the fluid equal those of the material, the maximum swelling results. When the differences in the parameter values of fluid and material are greatest the lowest swell occurs. This solubility parameter concept can be applied to mixtures also. The Hildebrand Linear volume blending rule can be used to calculate partial parameters for a multicomponent mixture (28). For a three component mixture:

$$\delta_D(1,2,3) = \phi_1 \delta_{D1} + \phi_2 \delta_{D2} + \phi_3 \delta_{D3}$$

$$\delta_P(1,2,3) = \phi_1 \delta_{P1} + \phi_2 \delta_{P2} + \phi_3 \delta_{P3}$$

$$\delta_H(1,2,3) = \phi_1 \delta_{H1} + \phi_2 \delta_{H2} + \phi_3 \delta_{H3}$$

where  $\phi$  is the volume fraction

TABLE 4. SOLUBILITY PARAMETERS

(Data from Refs. 27 and 28)

Material	Solubility Parameters (calories/cm <sup>3</sup> ) <sup>1/2</sup>			
	Overall $\delta$	$\delta_D$	$\delta_P$	Partial $\delta_H$
Benzene	9.2			
Toluene	8.9	8.8		1.0
Isooctane	7.0	7.0	0.7	0
Methanol	14.5	7.4	6.0	10.9
Ethanol	13.0	7.7	4.3	9.5
TBA <sup>1</sup>	10.5	7.4	2.7	7.0
MTBE <sup>2</sup>	7.4	6.9	1.1	2.3
Water	23.4	7.6	7.8	20.7
Fluorohydrocarbon rubber (Viton A) <sup>3</sup>	8.7	7.5	3.5	2.6
(Viton B) <sup>4</sup>	10.5	7.5	5.0	5.5
Fluorosilicone rubber (LS-63U) <sup>5</sup>	8.2			Bimodal swell <sup>6</sup>
Acrylonitrile/butadiene copolymer (Buna N, Nitrile)	8.8	7.5	3.5	3.0
Epichlorohydrin/ethylene oxide copolymer	9.2	8.8	2.0	2.0
Polyethylene	11.2	9.0	2.5	6.2
polymethyl methacrylate	10.6	9.1	4.0	3.5
polyurethane	7.9			
Nylon 66	9.5			
Cellulose	10.0			
Polyacrylonitrile	13.6			
Epoxy	15.65			
Polyvinyl chloride	15.4			
Polytetrafluoroethylene	10.9			
	9.7			
	6.2			

Footnotes for Table 4 are on the following page.

Footnotes for Table 4:

1. Tertiarybutyl alcohol.
2. 2,methyl,2-butyl ether
3. DuPont tradenama, a copolymer of vinylidene fluoride and hexafluoropropylene.
4. DuPont tradenama, a triopolymer of the two components in Viton A plus tetrafluoroethylene.
5. Dow trademark.
6. Copolymer (composed of two monomeric species) x-y have partial parameters and swelling behavior reflecting the properties of each monomeric species.

The avgas seal swelling problems can be associated with fuel aromatic content. The solubility parameters of the aromatic materials in most gasolines are  $\delta_D = 8.7$ ,  $\delta_P = 0.4$ ,  $\delta_H = 1.1$  (28). This is very close to those for toluene. The aliphatic components (paraffins, olefins and naphthenes) all have low, nearly equal solubility parameters. These average  $\delta_D = 7.0$ ,  $\delta_P = 0$ ,  $\delta_H = 0$ . These are also the solubility parameters for isooctane. This information supports the use of toluene and isooctane blends to study the volume change problem.

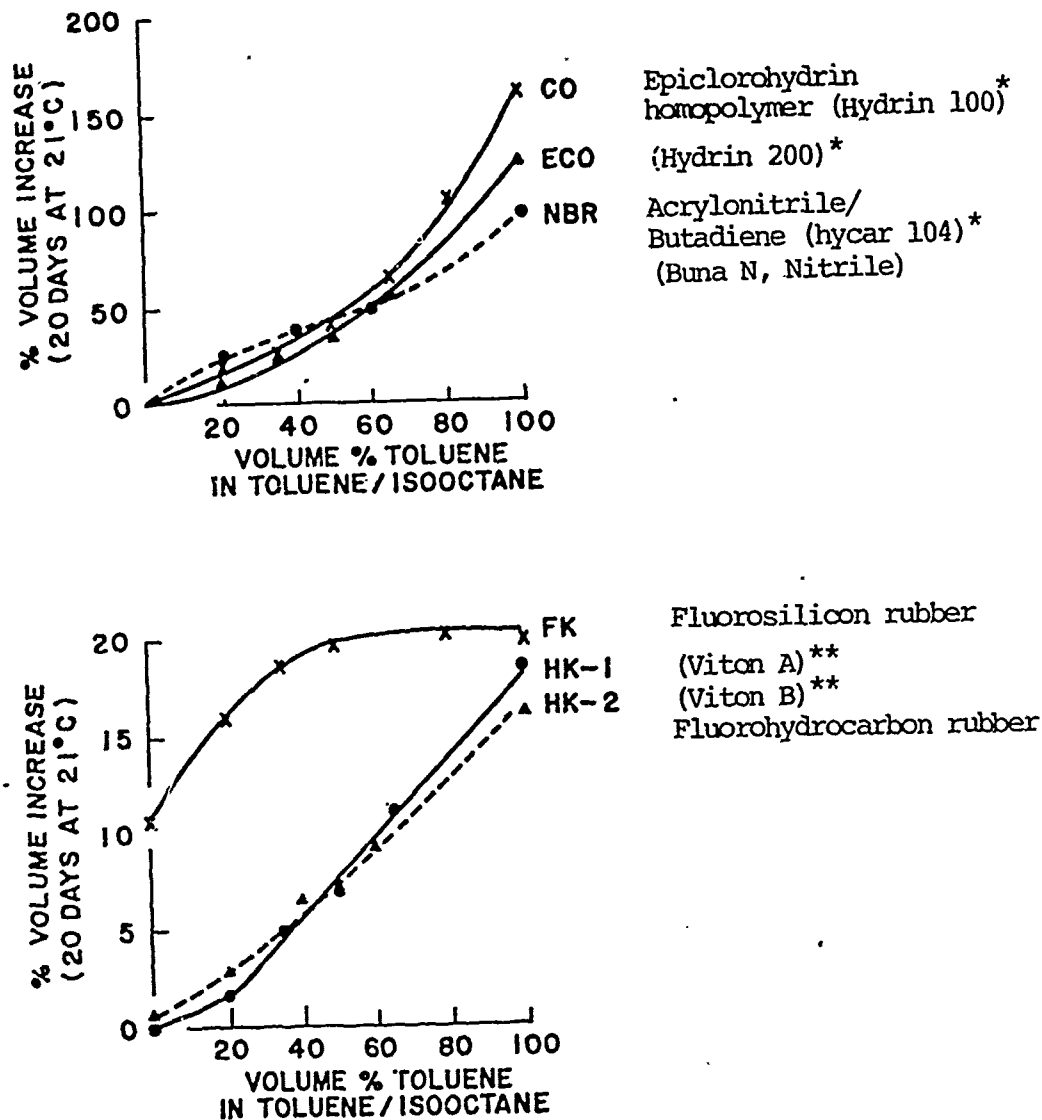
Nersasian (27) has soaked materials in a two component blend to study the problem. The two components were isooctane and toluene. Some results are shown in Figure 18. These indicate that many fuel system elastomers swell nearly linearly with increase in toluene concentration. This implies that an autogas with an aromatic content of 40% will probably cause swelling which is twice as great as that from a 20% aromatic avgas. MTBE (2,methyl,2-butyl ether) when tested in isooctane/toluene blends produced a moderate amount of swelling with concentrations likely to be present in autogas. The effects of alcohols on swelling behavior can be nearly as great as aromatics but are less consistent from compound to compound.

Problems have been experienced by the automotive industry recently related to chemical attack of autogas on fuel system elastomers. This has been traced to gasoline which has reacted with oxygen to form hydroperoxides and turned "sour." The hydroperoxides decompose forming free radicals which can cause reversion (chain breaking resulting in softening) or vulcanization (continued cross linking resulting in embrittlement). These large changes in physical properties are independent of those expected from solubility effects. The olefins in cracked gasoline are the least stable and the first to oxidize and the olefinic content of autogas is generally relatively high compared to avgas. Gasoline blended with alcohol also tends to be unstable. Fuel composition, storage time, exposure to heat, light and trace metals determine the amount of oxidation.

The non-metallic materials in current aircraft may experience damage from autogas which may, on occasion be "sour," contain very high percentages of aromatics, have MTBE or be contaminated with alcohol. Materials which can withstand these conditions are being developed for use in the automotive industry. The problems with the installation of these new materials in aircraft is that they must be capable of maintaining dimensions and properties over a wide variety of fuel types (high and low aromatics). A problem of retrofitting any aircraft for autogas use would be to identify susceptible materials and suitable replacements. Decisions must be made on a plane to plane basis from material information supplied by the manufacturers of the various non-metallic materials. This would be a formidable task since the materials themselves were selected initially based on performance specifications in avgas rather than on their detailed chemical composition. Thus different suppliers of the same part may provide somewhat different materials.

METALLIC MATERIALS. Corrosion and wear will be influenced most by the lead, sulfur, and halogen scavenger content of the fuel. Some of the halogen acids produced on combustion find their way into the crankcase and combine with water. This is a





\*R TM Goodrich  
 \*\*R TM DuPont

FIGURE 18. THE EFFECT OF TOLUENE/ISOOCTANE BLENDS AT 21°C ON THE VOLUME INCREASE OF SOME FUEL SYSTEM RUBBERS (Ref. 27)

particular problem in those engines which have high blowby rates. It has long been recognized that mineral acids and those formed from sulfur and halogens in gasolines are corrosive and promote wear and rust. Aviation mix is sold to be used with avgas and has 1.0 theory ethylene dibromide. ASTM specifications for avgas limit the scavenger content to this amount. Because in 1942 ethylene dibromide appeared to be both expensive and in short supply for the large amounts needed for automotive uses, a compromise was reached involving cost, scavenging effectiveness and corrosion. This was called motor mix. It contained tetraethyl and tetramethyl lead, 1.0 theory ethylene dichloride and 0.5 theory ethylene dibromide. This composition has been retained for almost 40 years. However, the ASTM specifications for autogas do not specify concentration of scavengers and this decision is left to the refiner. Some laboratory engine testing (30) under low temperature conditions (those in which the oil does not get hot enough to drive off moisture) indicated that the presence of the chlorine scavenger caused increased corrosion and wear. Journal bearings, cylinder walls, rings, and particularly hydraulic valve lifters were affected. Increased sulphur concentration in the fuel was shown to have a strong influence on wear and corrosion. This same testing indicated that cylinder bore and ring wear were nearly as great with an unleaded fuel as with the fuel using the motor mix. The mechanism for this was not known, but it may be related to cylinder wall washing by the fuel. Other testing done comparing aviation mix with motor mix under both high output and low temperature conditions in laboratory and automotive type multicylinder engines indicate about 50% lower engine wear with the aviation mix. Faster depletion of the alkaline reserve of the lubricating oil was also experienced. Once this reserve is depleted, corrosive wear can progress at a rapid rate. Leaded autogas use in aircraft engines would require more frequent oil changes, and the frequency of overhaul would most likely need to be increased.

The aspect of engine performance most suspect when changing tetraethyllead/scavenger combinations is intake and, particularly, exhaust valve durability. Valve durability is also a major problem when considering the use of unleaded fuels. Test data on the effects of scavenger type in automotive engines running under high output conditions tend to agree that the chlorine scavengers must be used with valve materials which are more resistant to hot corrosive attack. The valve and valve seat systems have been developed for optimum performance with the fuel with which they are intended to be used. Problems with valves usually occur quite gradually because of slow wear. The lead (and scavenger) content also seem to play an important role in the rate of valve deterioration. When the automotive industry switched to unleaded fuel use it was found that the valves receded into the valve seats in the absence of lead. Experiments have shown that very little antiknock was needed to protect the valves which were currently in use. Some reports indicated that as little as 0.07 gm lead/gal was needed. Also it has been reported that phosphorous additives were effective in reducing recession rate with these fuels (31). Moreover, lead antiknocks have a residual effect because they combine with deposits. If a leaded fuel is used occasionally with unleaded autogas and a phosphorous additive (also used to control deposit ignition) is used, then valve troubles in engines designed for 80/87 avgas may be minimized. The fuel survey data show that 5 out of the 25 samples of 80/87 have either no-lead or so little that they would

be under the maximum lead contents of unleaded autogas (0.05 gm/gal). However, since lead content of 80/87 avgas is variable some lead is passed through the engine from time to time and this appears sufficient to circumvent valve problems. Automotive catalytic converter poisoning limitations do not allow either lead or phosphorous to be included in unleaded autogas.

The use of leaded grades of autogas, desirable because of their lower cost, higher octane reserve, and lower aromatic content is less desirable in aircraft because of increased spark plug fouling, engine wear and particularly increased exhaust valve failures. Leaded autogas grades have been averaging about 2 gms/gal. lead with extremes to over 10 gms/gal. This is greater than the average amount in 100 LL, 1-1/4 gram an amount which has produced some adverse valve effects and increased spark plug fouling compared to grade 80/87.

#### GASOLINE STORAGE STABILITY.

Gasolines are subject to deterioration when exposed to the atmosphere by the action of oxygen. This may take place during manufacture, storage, and use, and the effect of deterioration may be serious insofar as product performance is concerned. Many variables affect the length of time that a gasoline can be stored without unacceptable deterioration. Today's gasolines, in particular autogas, are mixtures of a large number of different hydrocarbons. Not all hydrocarbons compounds are equally stable.

In general, cracking processes result in the introduction of olefins and diolefins into the gasolines. These compounds greatly reduce the oxidation stability of a fuel. Prior to the advent of cracking, gasolines were free of olefins and problems due to storage of the gasolines were minimal. Olefins are not found naturally in crude oil because they are unstable. The cracking process splits the larger hydrocarbon molecules of heavy residues into smaller components and although it provides gasoline at increased quantity and of higher octane quality, the oxidation stability of the fuel is in general seriously reduced.

The consequences of the reduced stability is the formation of gums and peroxides upon storage. Gum is a high boiling, sticky, viscous material which if present in high concentrations, may deposit in fuel tanks, fuel lines, carburetors, intake systems, including intake valves and in general cause malfunctioning in the engine. It is important that the gum formation in gasoline during storage be kept at a low level. ASTM specifications for gum appear elsewhere in this report. Gum is formed by the oxidation and polymerization of the unstable components in the gasoline. The nature and concentration of these deleterious materials vary with the source of the gasoline, i.e. type of crude and processing received. Different gasolines therefore can vary widely in their storage stability.

Whereas gasoline stability can be improved by various treatments such as caustic washing, acid washing, contact with absorbent solids such as activated clays, partial hydrogenation, etc. it is frequently more economical to add an

antioxidant. Excellent antioxidants are available and over the years there has been a shift in their use because of the changes in processing and composition of the gasoline. Antioxidants are very effective and their concentration can be varied depending on need.

Widespread adoption of catalytic cracking and catalytic reforming and the increasing use of alkylate in autogas have greatly increased the stability of modern gasolines. Unstable components such as those from thermal cracking and from polymer gasolines are disappearing from use. As a result of these changes, the stability problem and the amount and type of antioxidant needed in today's gasoline have also changed. In the past, the principal antioxidants have been the phenylene diamine or aminophenol types in addition to the alkylated phenols. Several factors have resulted in a gradual change from the phenylene diamine antioxidants to the alkylated phenols.

The gasolines of several years ago required relatively high concentration of antioxidants, for example, 12-50 lbs. active ingredient per 1,000 barrels, depending upon the type. The amine type additives tend to have an adverse effect on engine cleanliness, causing deposits in the intake manifold and in the crankcase area. Current gasolines use considerably less antioxidant in the 2-3 lbs/1,000 barrel range in order to provide adequate storage stability.

The presence of antioxidants in almost all commercial fuels has in the past provided a beneficial side effect by stabilizing the tetraethyllead antiknock in the fuel. In recent years decomposition of the lead antiknock has become the dominant stability problem. If the protection is inadequate and oxidation occurs, the hydrocarbon portion will contribute peroxides and gum while TEL decomposition will eventually produce an insoluble precipitate. The ill effects of gum have already been mentioned. The sole adverse effect of excessive TEL degradation is filter plugging either in the fuel distribution system or in the engine fuel system. Excessive amounts of precipitate can be formed from the decomposition of a comparatively small amount of TEL. The losses of TEL involved (frequently less than 1%) represent an insignificant proportion of the total and there is little loss of antiknock effect, even though there is a fair amount of precipitate in evidence. Peroxides formed do reduce antiknock quality however since these are proknock compounds.

The changes in gasoline composition in recent years has reduced the reliability of the ASTM induction period as a predictor of fuel stability. ASTM Test D525-55, Oxidation Stability of (Gasoline Induction Period Method) has in the past been quite reliable in predicting oxidation stability of gasoline. The marked decrease in the reliability of this method for predicting storage behavior has resulted in a gradual lessening of antioxidant use until occasionally the point is approached where the amount of antioxidant required for the stabilization of the TEL in the fuel is not being provided.

Temperature has a very strong influence on stability. Peroxide formation (with

accompanying gum formation and octane reduction) is a chain reaction which occurs after an induction period. Once this chain reaction begins, deterioration of the gasoline proceeds at an accelerated rate. The induction period (the time period that the gasoline can be stored before the chain reaction begins) very likely follows a common empirical chemical rate equation, where the rate of reaction increases exponentially with absolute temperature.<sup>1</sup> It is this exponential relationship which makes possible accelerated testing where years are compressed into hours at elevated temperatures. Figure 19 shows both the chain reaction effect and the effect of temperature on induction period for avgas undergoing accelerated testing. Under actual storage conditions, oxygen concentration, exposure to catalytic materials, light and contaminants all effect the induction period. The primary value of the oxidation stability tests for autogas<sup>2</sup> and avgas<sup>3</sup> is to provide a quick indication of some abnormal occurrence in refinery operation. It has poor correlation to the actual storage stability of today's gasolines. A much more accurate test (but much less convenient) is laboratory storage at 110°F. A rule of thumb regarding this test is that 1 week at 110°F is approximately equivalent to 1 month of more normal storage (43). Figure 20 shows how the time to failure at 110°F of various autogas samples varies. This figure also shows the lead precipitation problems experienced with the more common non-thermal blends. Thermal blends (those containing thermally cracked, reformed, or polymerized components) are no longer common because these processes are not as economical as the catalytic (non-thermal) ones.

A May 1974 Exxon technigram "Gasoline Storage Life" (39) on autogas, suggest "...if gasoline is stored for over six months additional oxidation inhibitors should be added to the fuel. The normal antioxidant and metal deactivator treating levels are 2 to 4 pounds per 1000 barrels. As a rule of thumb, these levels should be doubled, and the gasoline should be checked for increased gum content at quarterly intervals." While Maxwell Smith in his book, "Aviation Fuel" (23) says of avgas ... "The specification units for dissolved gum and precipitate are chosen to provide satisfactory storage stability, this means at least two years under the worst conditions, i.e., in the tropics, and considerably longer in temperate climates."

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<sup>1</sup>Arrhenius Equation:  $k = A e^{-\Delta E^*/R_0 T}$

where k is the temperature function, A = constant for each reaction,  $\Delta E^*$  = activation energy (constant),  $R_0$  = ideal gas constant, T = absolute temperature.

<sup>2</sup>ASTM D525 Oxidation Stability of Gasoline (Induction Period Method) (for autogas), 100 ml sample in glass container, 212°F, 100° psi oxygen pressure, induction period = minutes to pressure break point (pressure falling at greater than 2 psi/15 min.).

<sup>3</sup>ASTM D873 Oxidation Stability of Aviation Fuels/Potential Residue Method, 200 ml sample in glass container, 212°F, 100 psi oxygen pressure, exposure for specified period of time (5 or 16 hrs.) Measure for gum and precipitate content-- shows failure due to both oxidation and TEL breakdown.

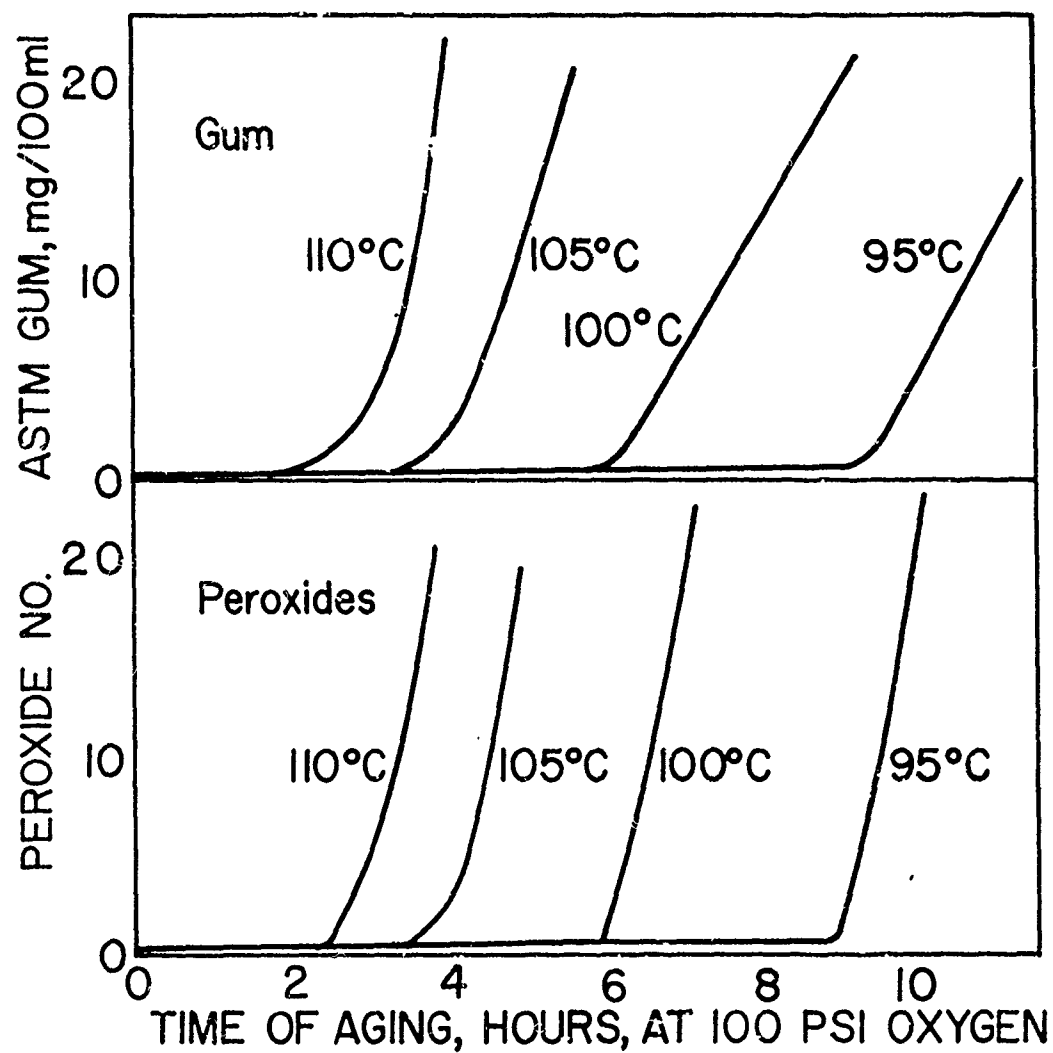


FIGURE 19. EFFECT OF TEMPERATURE ON STABILITY OF TYPICAL LEADED AVIATION GASOLINE (REFERENCE 44)

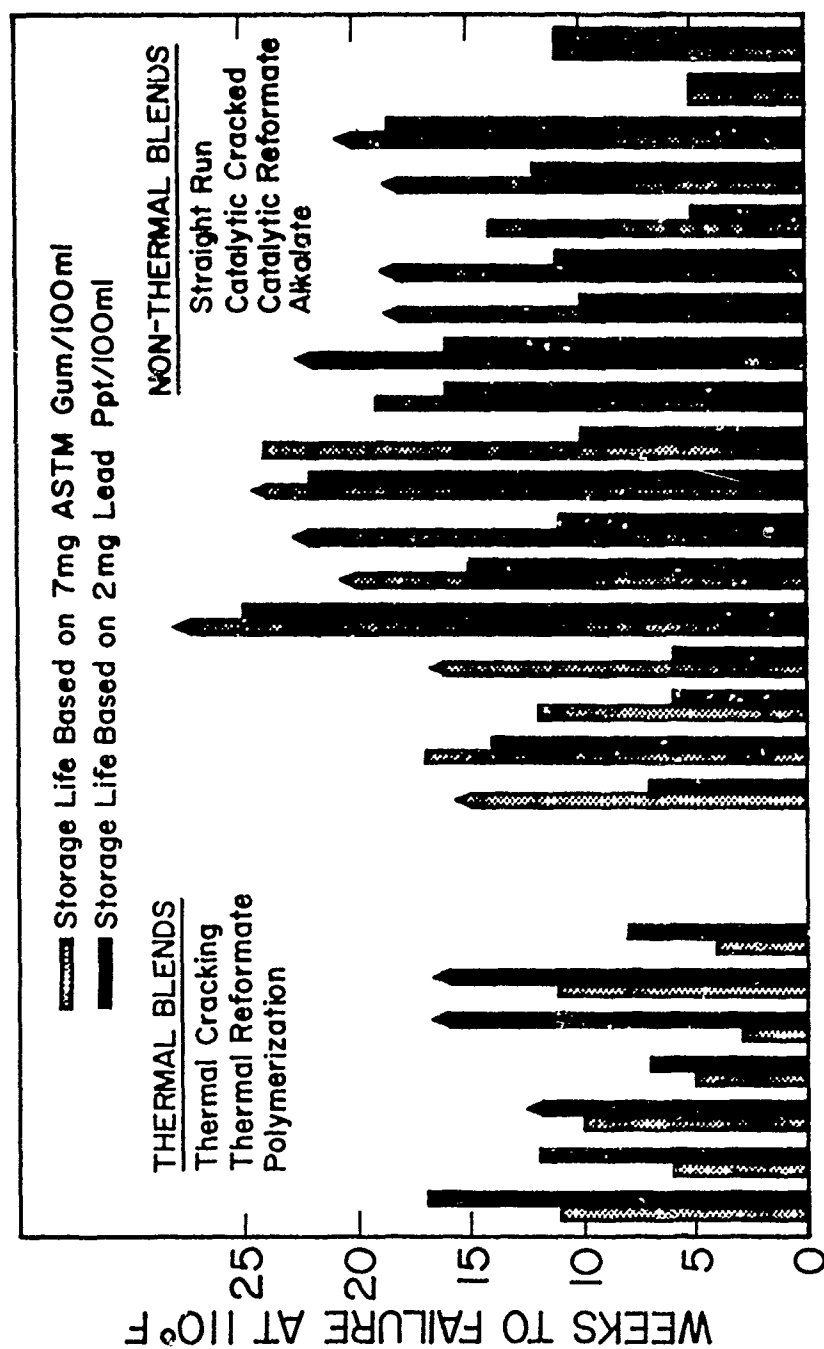


FIGURE 20. TYPE OF FAILURE IN 110° F STORAGE OF COMMERCIAL AUTOGAS  
 TEL CONTENT 2.6 to 3.2g Pb/gal. (Reference 45)

Footnote K of ASTM D910 says that by agreement between purchaser and supplier the oxidation stability of avgas test (potential residue) can be run to 16 hours instead of 5 hours. In this case a doubling of antioxidant to 8.4 lb. per 1000 bbl is permitted.

Whether or not storage stability would be a greater problem with autogas could also depend on its rate of use. If the storage time is relatively long, which is the case for some avgas stored at small fields, then the problems arising from instability are potentially serious for users of the fuel. On the other hand, if automobiles and aircraft are fueled from the same tank, then storage stability would probably not be a problem since the rate of use would be high.

#### ADDITIVES FOR PETROLEUM PRODUCTS

Additives are chemical compounds added in small quantities (in most cases less than 1%) to the primary product. However, some additives are used in automotive lubricants at concentrations much higher than 1%. In the case of fuels, a chemical used in such high concentration (5% or more) would probably be considered a blending agent rather than additive.

An additive can be defined as a chemical compound which imparts new and desirable properties either not originally in a product or not obtained by processing. It can also be used to produce superior properties at lower cost and has been shown to conserve crude oil. As a rule, different chemicals are used to obtain different properties. These compounds must be chemically active to perform their function, hence they can affect or interact with each other when used in the same medium. Additives can complement or supplement each other, or affect one another adversely.

Examples of additive classes used in autogas, avgas and lubricating oil are shown in Tables 5, 6 and 7 from Reference (32).

#### ADDITIVES FOR LUBRICANTS.

Additives are used in lubricants to a very considerable extent and probably to a greater degree than any other group of petroleum products. The purpose of many of these additives is to counteract the effects of the chemically active products of combustion which blow by the piston into the crankcase. With the high level of additives in automotive lubricants and small piston clearances (low blowby rates), autogas containing a broader range of composition than avgas can be used with acceptable engine wear rates. The components of the fuel which most affect lubricant performance are sulfur, TEL and its scavengers, heavy ends and gums, compounds more prevalent in autogas. Additives which contain ash (metallic elements) cannot be used in lubricants for aircraft engines which burn significant amounts of their lubricating oil. This is because the deposits resulting from ash-containing additives have a strong tendency to cause preignition at high engine speeds and



TABLE 5. EXAMPLES OF ADDITIVES USED IN AUTOGAS

<u>Additive Type</u>	<u>Chemical Composition</u>	<u>Purpose</u>
Antiknock agent	Tetraethyl lead Metal carbonyls	Prevent engine knocking and to increase octane number.
Scavenger	Ethylene dihalides	React with the lead residues.
Antioxidant	2,6 Di-tert. butyl-4-cresol N,N-N' Di-sec. butyl-4-phenylenediamine	Prevent gum formation.
Metal deactivator	Disalicylidene propylenediamine	Overcomes catalytic effects of dissolved copper.
Corrosion inhibitor	Ammonium sulfonates	Prevent corrosion in carburetor.
Anti-icing agent	Dimethylformamide alcohols	Prevent stalling due to icing.
Upper-cylinder lube	Light lubricating oils	Minimize intake valve deposits. Lubricate top ring area.
Deposit Modifier	Tributyl phosphite	Minimize glow in combustion chamber.
Dye	p-Dimethylaminoazobenzene 1,4-Dialkylaminoanthraquinone	Impart color for identification.
Detergent	Amine phosphonates	Provide cleanliness to the intake system and carburetor.

TABLE 6. EXAMPLES OF ADDITIVES USED IN AUTOMOTIVE LUBRICATING OILS

<u>Additive Type</u>	<u>Chemical Composition</u>	<u>Purpose</u>
Viscosity index improver	Methacrylate polymers, butylene polymers	Lower the rate of change of viscosity with temperature.
Pour point depressant	Alkylated naphthalene	Decrease pour point of oil.
Detergent dispersant	Alkyl P <sub>2</sub> S <sub>5</sub> products, metal sulfonates, alkylpolyamide, metal alkyl phenolates	Keep insolubles in suspension and maintain cleanliness.
Oxidation inhibitor	Zinc dialkyldithiophosphate	Retard oxidation of oils.
Rust inhibitor	Alkylamines	Prevent rusting of ferrous metals.
Corrosion inhibitor	Basic metal sulfonates	Prevent acidic materials from attaching to metal surfaces.
Extreme pressure agent	Sulfurized olefins, chlorinated paraffins	Prevent seizure of metal surfaces.
Foam inhibitor	Silicone polymers	Decrease tendency to foam.
Antiscuff-wear agent	Metal salts of alkyl acid phosphates.	Provide chemical polishing and reduce wear.

TABLE 7. EXAMPLES OF ADDITIVES USED IN AVGAS

<u>Product</u>	<u>Additive Type</u>	<u>Chemical Composition</u>	<u>Purpose</u>
Aviation gasoline	Antioxidant	2,6 Di-tert-butyl-p-methylphenol	Arrest gum formation.
	Corrosion inhibitor	Esters of fatty acids	Arrest rust.
	Octane improver	Tetraethyl lead	Increase octane number.
	Dye	Organic compound	Identification.
	Metal deactivator	None	
	Corrosion inhibitor	None <sup>a</sup>	
	Icing inhibitor	None <sup>b</sup>	

a. Optional in U.S. military avgas

b. Ethylene glycol monomethyl ether—optional.

loads. Additives, particularly those designed to cope with automotive gasoline are discussed briefly below. Given also are some details of standard automotive testing required to ensure that lubricants are compatible with autogas in automotive engines.

ANTIOXIDANTS. Antioxidants prevent oils from oxidizing, particularly under prolonged exposure to high temperatures and in the presence of catalytic metals. Oil oxidization can produce undesirable sludge and varnish deposits, corrosive acids, and excessive oil thickening - all of which can lead to shorter engine life. Zinc dialkyl dithiophosphate is the most widely used antioxidant. Internal combustion engines are quite effective oxidizing machines since the oil in these engines is violently aerated at high temperatures for relatively long periods of time usually in the presence of metals such as copper and iron that act as catalysts. The source of these metallic accelerators may be the engine itself, or contaminants that enter the engine. Sludge, which is principally a combination of combustion products and unburned fuel and oil residues, can also catalyze the oxidation reaction.

Aminophenols are also used as oxidation inhibitors in motor oils, but not to the same extent as zinc dithiophosphate as will be shown later. Zinc dithiophosphate imparts additional beneficial properties to the motor oil by inhibiting corrosion and wear.

CORROSION INHIBITERS. Corrosion inhibitors prevent attack on non-ferrous metals such as engine bearings by forming a protective film on the metal surface. Zinc dithiophosphate and other chemicals provide anticorrosion protection.

ANTI-WEAR AGENTS. Anti-wear agents prevent or reduce wear of heavily loaded engine parts, such as cams and lifters. They are also known as extreme pressure agents. They concurrently reduce friction somewhat. Zinc dialkyl dithiophosphate also provides this function. The zinc dithiophosphate and other compounds of phosphorus, sulfur and chlorine used as anti-wear agents are present in concentrations sufficient to control corrosion and oxidation.

DETERGENTS. Detergents tend to eliminate high temperature engine deposits. These high temperature deposits on the piston and in the ring belt zone are harmful because they interfere with the sealing action of the rings thus causing a loss in performance and an increase in oil consumption. Typical detergent additives are barium, calcium sulfonates, phenates or phosphonates. These additives not only prevent deposits from forming on engine surfaces, but they also remove previously formed deposits.

DISPERSANTS. Dispersants are blended into motor oils to keep engines clean by holding in suspension the insoluble products of oil oxidation and fuel combustion formed during low and medium temperature engine operation. The contaminants in suspension are then drained from the engine with the oil. Without this cleaning and dispersant action, such contaminants would tend to settle out of the oil

onto engine parts. Since dispersant additives are soluble in oil, they keep the sludge particles separated and suspended in the oil in a form fine enough so they are not trapped by the oil filter.

Ashless dispersants are popular because of their high effectiveness in handling low temperature sludge in passenger car operation. Some ashless compounds qualify as multipurpose additives by improving viscosity index while acting as dispersants to control sludge and deposits. Because of their ashless nature they are one of the few additives used in some aviation piston engine oil.

Principal deleterious effects of low temperature sludge are ring plugging, plugging of oil screens, and other oil passages, resulting in oil starvation to critical engine areas. Engine failure can occur due to starvation of oil in critical areas.

VISCOSITY INDEX IMPROVERS. An important property of oil is the rate at which its viscosity changes with changes in temperature. This property is usually expressed by viscosity index (VI), an arbitrary number that describes the relative viscosity-temperature characteristics of an oil by a single number.

A VI improver is usually desirable in a motor oil since this material reduces the decrease in the viscosity of an oil with increase in temperature. Thus a single oil can be used over a much wider range of ambient temperatures. Such an oil not only provides easier starting, better lubrication, and less power loss at low temperature (by minimizing viscosity drag), but also reduces oil consumption and lubricates better at high temperature by maintaining a more viscous film of oil on moving parts.

This class of additive is used extensively in motor oils to increase viscosity beyond that which could be obtained by ordinary refining methods. Refiners often process oil to an intermediate VI quality rather than add an VI improver to reach the final level. These additives are essential ingredients in multigrade oils.

RUST INHIBITORS. Iron and steel parts will rust if they are not adequately protected from the chemical effects of water and acids. Such rust is especially critical in the close dimensional tolerance of some operating parts of an engine, such as hydraulic valve lifters. Rusting can be particularly troublesome during engine storage or as a result of short trip operation. Although petroleum oils do have some natural protection against rusting, they do not have sufficient anti-rust properties under most operating conditions. Therefore oil additives must be used to supply final protection. These additives usually function by neutralizing harmful acids or by forming a water and acid repellant layer on the surface of the metal. Some of these additives are multifunctional and can also provide detergent action as well as rust protection.

POUR POINT DEPRESSANTS. The pour point of an oil is defined as the lowest temperature at which a motor oil will flow. If the pour point is too high, bearing oil starvation during cold weather operation can cause bearing failure. Wax content

of the oil is the major variable affecting pour point. Wax raises the pour point by precipitating in a honeycomb-like structure during cooling, thus inhibiting flow.

The wax content of an oil can be reduced to a tolerable level by processing, but extensive dewaxing is costly. Therefore refiners frequently use pour point depressants as an economical means of producing oils of low pour point without severe dewaxing. The pour point depressants currently marketed are effective at very small concentrations (from 0.02 to 0.2 weight percent). The actual amount used depends on oil composition (selection of blending stocks), the degree of process, dewaxing, and the pour point desired. Most of the popular VI improvers also effectively lower the pour point.

Pour point depressants probably achieve their performance by preventing the tiny wax crystals from agglomerating to form the matrix that traps the oil and holds it in a semi-solid condition.

ANTI-FOAM AGENTS. The environment in the engine crankcase tends to promote motor oil foaming. As the oil circulates through the engine lubricating system, it becomes thoroughly mixed with engine blowby gases and air drawn in through the breather system. Considerable amount of the oil leaves the connecting rod bearing area by being thrown off against the wall of the block and crankcase, thus subjecting it to break-up and exposure to gases. This continuous aeration can produce oil foaming as well as oil oxidation.

Excessive foaming is undesirable because it can impair engine operation by vapor locking the oil pump or reducing the amount of available lubricant at critical points. Foam can also cause a faulty reading of the oil level in the sump. Only trace amounts (2-10 ppm) of certain chemicals are needed to eliminate the foaming tendency of most oils.

ASHLESS ADDITIVES. There is incentive to reduce both octane requirement increase and sludge deposits in light-duty passenger car operation and to combat destructive type pre-ignition in heavy-duty truck operation. This has led to the development of ashless oil additives. These additives differ from the conventional additives in that they do not contain high melting point metallic compounds which tend to form engine deposits that cause preignition.

Among the current available ashless additives are: ashless dispersants and antioxidants. Although not in universal use at the present time, these new additives are finding wider acceptance and have made possible the marketing of oil with reduced ash content. The only additives used in aviation oils are ashless dispersants and antioxidants.

ADDITIVE CONCENTRATION. Concentration of additives in motor oils can vary considerably depending on the selection of base stocks, crude source, and viscosity and service classifications that the finished oil must satisfy. Generally, more additives

are used as the viscosity index level of the oil is increased, or as the API service classification (see Table 8) is made more severe. Additive concentration is based on need to satisfy a given performance. Additive content can be as high as 20% by volume in a high performance oil such as MS grade.

A summary of the various ASTM tests for automotive oils is given in Table 8. Many of these tests are designed to explore problems arising from autogas properties. No comparable tests have been established for aircraft engines. The manufacturers have developed their engines to certify with the ashless oils marketed for aircraft. The low sulfur and low volume of heavy ends in avgas coupled with limited use of the bromine scavenger provide a relatively easy task for the lubricant.

#### ADDITIVES FOR GASOLINE

Today's gasolines are carefully blended using products from a variety of crude oils and refining processes. Processing includes catalytic cracking, catalytic reforming, polymerization, alkylation, hydrocracking, etc. Gasoline produced today bears little resemblance to the forerunners of years ago when most gasolines were produced either by straight distillation to separate the gasoline fractions from the whole crude oil or by thermal cracking of heavy fractions to convert them to hydrocarbons in the gasoline boiling range. Only a few of the above refining processes were commercial when aviation gasoline specifications were established. Although many hydrocarbons contained in aviation gasoline when the specifications were established were available, they were not necessarily produced by the above mentioned processes.

Today's refining processes have been developed to perform one or more of the following functions: 1) increase the gasoline yield from a barrel of crude, 2) raise the antiknock qualities of the gasoline, or 3) convert the gases to liquid hydrocarbons boiling in the gasoline range. In catalytic processing the catalysts and operating conditions are changed so as to maximize either gasoline or middle distillates.

The demands of the modern highly efficient gasoline engine exceeds what the refining processes alone can give. Chemical compounds are required to produce gasoline qualities needed for these engines. Additives and modern refining methods have been combined to give modern gasoline good service performance.

ANTIKNOCK COMPOUNDS. Engine knock or detonation is well known and fairly well understood. Knocking causes a very rapid pressure rise and high frequency shock waves that produce a sharp metallic noise in the engine. Knocking also can cause loss of power, poor fuel economy, and higher temperatures in the engine. Severe knock also tends to increase piston ring wear and to cause overheating of valves, spark plugs, and pistons thereby shortening their service life. In some cases, severe knock has a tendency to promote destructive or runaway preignition which can cause engine failure in a relatively short time. Failure can result from holes burned through pistons, broken spark plug insulators, and/or badly burned or

TABLE 8. ASTM TESTS FOR MOTOR OILS (1978 SAE HANDBOOK)

DESIGNATION, IDENTIFICATION AND DESCRIPTIONS OF CATEGORIES

Letter Designation	API Engine Service Description	ASTM Engine Oil Description	Letter Designation	API Engine Service Description	ASTM Engine Oil Description
SA	Utility Gasoline and Diesel Engine Service Service typical of engines operated under such mild conditions that the protection afforded by compounded oils is not required. This classification has no performance requirements.	Oil without additive except that it may contain pour and/or foam depressants.	CA for Diesel Engine Service	Light Duty Diesel Engine Service Service typical of diesel engines operated in mild to moderate duty with high quality fuels. Occasionally has included gasoline engines in mild service. Oils designed for this service were widely used in the late 1940s and 1950s. These oils provide protection from bearing corrosion and from high temperature deposits in normally aspirated diesel engines when using fuels of such quality that they impose no unusual requirements for wear and deposit protection.	Oil meeting the requirements of MIL-L-2104A. For use in gasoline and naturally aspirated diesel engines operated on low sulfur fuel. The MIL-L-2104A Specification was issued in 1954.
SB	Minimum Duty Gasoline Engine Service Service typical of engines operated under such mild conditions that only minimum protection afforded by compounding is desired. Oils designed for this service have been used since the 1930s and provide only antiscuff capability, and resistance to oil oxidation and bearing corrosion.	Provides some antioxidant and antiscuff capabilities.			
SC	1964 Gasoline Engine Warranty Service Service typical of gasoline engines in 1964-1967 models of passenger cars and trucks operating under engine manufacturers' warranties in effect during those model years. Oils designed for this service provide control of high and low temperature deposits, wear, rust, and corrosion in gasoline engines.	Oil meeting the 1964-1967 requirements of the automobile manufacturers. Intended primarily for use in passenger cars. Provides low temperature antisludge and antirust performance.	CB for Diesel Engine Service	Moderate Duty Diesel Engine Service Service typical of diesel engines operated in mild to moderate duty, but with lower quality fuels which necessitate more protection from wear and deposits. Occasionally has included gasoline engines in mild service. Oils designed for this service were introduced in 1949. Such oils provide necessary protection from bearing corrosion and from high temperature deposits in normally aspirated diesel engines with higher sulfur fuels.	Oil for use in gasoline and naturally aspirated diesel engines. Includes MIL-L-2104A oils where the diesel engine test was run using high sulfur fuel.
SD	1968 Gasoline Engine Warranty Maintenance Service Service typical of gasoline engines in 1968 through 1970 models of passenger cars and some trucks operating under engine manufacturers' warranties in effect during those model years. Also may apply to certain 1971 and/or later models, as specified (or recommended) in the owners' manuals. Oils designed for this service provide more protection against high and low temperature engine deposits, wear, rust, and corrosion in gasoline engines than oils which are satisfactory for API Engine Service Classification SC and may be used when API Engine Service Classification SC is recommended.	Oil meeting the 1968-1971 requirements of the automobile manufacturers. Intended primarily for use in passenger cars. Provides low temperature antisludge and antirust performance.	CC for Diesel Engine Service	Moderate Duty Diesel and Gasoline Engine Service Service typical of lightly supercharged diesel engines operated in moderate to severe duty and has included certain heavy duty, gasoline engines. Oils designed for this service were introduced in 1961 and used in many trucks and in industrial and construction equipment and farm tractors. These oils provide protection from high temperature deposits in lightly supercharged diesels and also from rust, corrosion, and low temperature deposits in gasoline engines.	Oil meeting requirements of MIL-L-2104B. Provides low temperature antisludge, antirust, and lightly supercharged diesel engine performance. The MIL-L-2104B specification was issued in 1964.
SE	1972 Gasoline Engine Warranty Maintenance Service Service typical of gasoline engines in passenger cars and some trucks beginning with 1972 and certain 1971 models operating under engine manufacturers' warranties. Oils designed for this service provide more protection against oil oxidation, high temperature engine deposits, rust, and corrosion in gasoline engines than oils which are satisfactory for API Gasoline Engine Warranty Maintenance Classification SD or SC and may be used when either of these classifications are recommended.	Oil meeting the 1972 requirements of the automobile manufacturers. Intended primarily for use in passenger cars. Provides high temperature antioxidant, low temperature antisludge, and antirust performance.	CD for Diesel Engine Service	Severe Duty Diesel Engine Service Service typical of supercharged diesel engines in high speed, high output duty requiring highly effective control of wear and deposits. Oils designed for this service were introduced in 1955, and provide protection from bearing corrosion and from high temperature deposits in supercharged diesel engines when using fuels of a wide quality range.	Oil meeting Caterpillar or Tractor Co. certification requirements for Superior Lubricants (Series 3) for Caterpillar diesel engines. Provides moderate to superior diesel engine performance. The certification of Series 3 oil was established by Caterpillar or Tractor Co. in 1955. The related MIL-L-45199 specification was issued in 1958.



TABLE 8. ASIM TESTS FOR MOTOR OILS (1978 SAE HANDBOOK) (Continued)

TEST TECHNIQUES AND PRIMARY PERFORMANCE CRITERIA							
Letter Designation	Test Techniques <sup>a</sup>	Primary Performance Criteria <sup>b</sup>		Letter Designation	Test Techniques <sup>a</sup>	Primary Performance Criteria <sup>b</sup>	
SA	None	None		SE	Sequence IIC	per rating method of CRC Manual No. 9	9.3
SB	L-4 or L-38 <sup>b</sup> Sequence IV	Bearing weight loss, mg, max Cam scuffing Lifter scuff rating, max	L-4 500 L-38 500 None 2			Avg oil ring and varnish rating, min	6.0
SC	Sequences IIA and IIA	Cam and lifter scuffing Avg cam plus lifter wear, in max	None 0.0025			Avg sludge rating, min	9.0
		Avg rust rating, min	8.2			Ring sticking	None
		Avg sludge rating, min	9.5			Lifter sticking	None
		Avg varnish rating, min	9.7			Scuffing and wear at 64 test h	
	Sequence IV	Cam scuffing	None			Cam or lifter scuffing	None
	Sequence V	Lifter scuff rating, max	2		Sequence VC	Cam plus lifter wear, in Average	0.0010
		Total engine sludge rating, min	40			Maximum	0.0020
		Avg piston skirt varnish rating, min	7.0			Avg engine sludge rating, min	8.5
		Total engine varnish rating, min	35			Avg piston skirt varnish rating, min	
		Avg intake valve tip wear, in max	0.0020			per rating method of Ford Motor Co.	8.2
		Ring sticking	None			per rating method of CRC Manual No. 9	7.9
		Oil ring clogging, %, max	20			Avg engine varnish rating, min	8.0
		Oil screen plugging, %, max	20		L-38	Oil screen clogging, %, max	5
	L-38 <sup>c</sup>	Bearing weight loss, mg max	50			Oil ring clogging, %, max	5
	L-1 (0.95% min sulfur fuel)	Groove No. 1 (top) carbon fill, % vol, max	25	CA	L-4 or L-38 <sup>b</sup>	Compression ring sticking	None
		Groove No. 2 and below	Essentially clean			Bearing weight loss, mg, max	L-4 120-135 L-38 50
SD	Sequences IIB and IIB	Cam and lifter scuffing Avg cam and lifter wear, in max	None 0.0030		L-1 (0.35% min sulfur fuel)	Groove No. 1 (top) carbon fill, % vol, max	9.0 9.0
		Avg rust rating, min	8.8			Groove No. 2 and below	25
		Avg sludge rating, min	9.6				Essentially clean
		Avg varnish rating, min	9.6	CB	L-4 or L-38 <sup>b</sup> L-1 (0.95% min sulfur fuel)	Same as CA Same as CA, except Groove No. 1 (top) carbon fill, % vol, max	30
	Sequence IV	Cam scuffing	None				
	Sequence VB	Lifter scuff rating, max	1	CC	L-38	Bearing weight loss, mg, max	50
		Total engine sludge rating, min	42.5			Piston skirt varnish rating, min	9.0
		Avg piston skirt varnish rating, min	8.0				
		Total engine varnish rating, min	37.5		LTD or Modified	Piston skirt varnish rating, min	LTD Mod. LTD
		Avg intake valve tip wear, in max	0.0015		LTD <sup>b</sup>	Total engine varnish rating, min	7.5 7.5
		Oil ring clogging, %, max	5			Total engine sludge rating, min	— 42
		Oil screen plugging, %, max	5			Oil ring plugging, %, max	35 42
	L-38 <sup>c</sup>	Bearing weight loss, mg max	40			Oil screen clogging, %, max	25 10
							25 10
	L-1 (0.95% min sulfur fuel) <sup>c</sup> or L-H <sup>c</sup>	Groove No. 1 (top) carbon fill, % vol, max	L-1 25 L-H 30		Sequence IIA or IIB <sup>b</sup> L-H	Avg engine rust rating, min	IIA IIB
		Groove No. 2 lacquer coverage, % area, max	— 50			Groove No. 1 (top) carbon fill, % vol, max	8.2 8.2
		Groove No. 2 and below	Essentially clean			Groove No. 2 lacquer coverage, % area, max	30
		Land No. 3 and below	—			Land No. 3 and below	50
	Falcon <sup>c</sup>	Avg engine rust rating, min	9.0				Essentially clean
				CD	I-D	Groove No. 1 (top) carbon fill, % vol, max	75
			IIIB IIC			Groove No. 2 and below	Essentially clean
SE	Sequence IIB or IIC	Avg engine rust rating, min	8.9 8.4		I-G	Groove No. 1 (top) carbon fill, % vol max	60
	Sequence IIC	Viscosity increase at 100°F and 40 test h, %, max	400			Land No. 2 carbon and lacquer coverage, % area, max	50
		Avg engine ratings at 64 test h				Groove No. 2 carbon and lacquer coverage, % area, max	30
		Avg piston skirt varnish rating, min				Land No. 3 and below	Essentially clean
		per rating method of CRC Manual No. 1	9.5		L-38 <sup>c</sup>	Bearing weight loss, mg, max	50
						Avg piston varnish rating, min	9.0

TABLE 8. ASTM TESTS FOR MOTOR OILS (1978 SAE HANDBOOK) (Continued)

## GASOLINE ENGINE TESTS

Test	Engine			Time		Load		Fuel Flow		Speed, rpm	Temperature			
	Type	Displacement		Total, h	Each Phase	bhp	kW	lb/h	N/h		Coolant		Oil	
		in <sup>3</sup>	cm <sup>3</sup>								°F	°C	°F	°C
L-4	L6	216	3540	36		30	22.1			3150	200	93.3	280	137.8
L-3B	Single	42.5	696	40				4.5-5.0	20.0-22.2	3150	200	93.3	290	143.3
L-3B (Revised)	Single	42.5	696	40				4.5-5.0	20.0-22.2	3150	200	93.3	290	143.3
LTD	Single	42.5	696	180	3 h 1 h			4.7 4.7	20.9 20.9	1800 1800	120 200	48.9 93.3		
Modified LTD	Single	42.5	696	180	3 h 1 h			4.7 4.7	20.9 20.9	1800 1800	120 200	48.9 93.3		
Sequence I	V8	394	6456	5	10 min	2	1.5			2500	95	35	120	48.9
Sequence II	V8	394	6456	30	3 h	25	18.6			1500	95	35	120	48.9
Sequence III	V8	394	6456	40		85	63.4			3400	200	93.3	265	129.4
Sequence IIA	V8	394	6456	22	20 h 2 h	25 25	18.6 18.6			1500 1500	95 120	35 48.9	120 120	48.9 48.9
Sequence IIA	V8	394	6456	40		85	63.4			3400	200	93.3	265	129.4
Sequence IIB	V8	425	6964	24	20 h 2 h 2 h	25 25 100	18.6 18.6 74.6			1500 1500 3300	105 120 200	40.6 48.9 93.3	120 120 275	48.9 48.9 135.0
Sequence IIC	V8	425	6964	32	28 h 2 h 2 h	25 25 100	18.6 18.6 74.6			1500 1500 3600	110 120 700	43.3 48.9 93.3	120 120 260	48.9 48.9 126.7
Sequence IIB	V8	425	6964	56	7 h 7 h	100 100	74.6 74.6			3600 3600	150 200	65.6 93.3	200 275	93.3 135.0
Sequence IIC	V8	425	6964	64		100	74.6			3000	245	118.3	300	148.9
Sequence IV	V8	361	5916	24	2 h	None	None			3600	180	82.2	220	104.4
Sequence V	V8	368	6030	192	45 min 2 h 75 min	None 105 105	None 78.3 78.3			500 2500 2500	115 125 170	46.1 51.7 76.7	120 175 205	48.9 79.4 96.1
Sequence VB	V8	289	4736	192	45 min 2 h 75 min	None 86.6 86.6	None 64.6 64.6			500 2500 2500	115 125 171	46.1 51.7 77.2	120 175 201	48.9 79.4 93.9
Sequence VC	V8	302	4949	192	2 h 75 min 45 min	86.6 86.6 2	64.6 64.6 1.5			2500 2500 500	135 170 115	57.2 76.7 46.1	175 200 120	79.4 93.3 48.9
Falcon	L6	170	2786	55	45 min 2 h	None 30.9	None 23.0			500 2500	115 125	46.1 51.7	120 175	48.9 79.4

Test	Air-Fuel Ratio	Procedure Reference (See Refs. 1, 3-5)	Evaluation					Oil Categories Defined
			Rust and Corrosion	Sludge	Varnish	Wear	Other	
L-4	14.5	FTMS 791A - FTM 3402		X	X		Bearing corrosion	CA, CB, SB
L-3B	14.0	FTMS 791B - FTM 3405.1		X	X		Bearing corrosion	CA, CB, CC, SB, SC, SD
L-3B (Revised)	14.0	FTMS 791B - FTM 3405.2		X	X		Bearing corrosion	CD, SE MR-L-2104C, MR-L-46152
LTD	14.5	FTMS 791B - FTM 349.1		X	X			CC
Modified LTD	15.25 15.25	FTMS 791B - FTM 348.2		X	X			CC
Sequence I	14.0	ASTM STP 315, 315A	X					MS (obsolete)
Sequence II	14.0			X	X			MS (obsolete)
Sequence III	15.0							MS (obsolete)
Sequence IIA	12.0 12.0	ASTM STP 315B, 315C	X					CC, SC
Sequence IIA	16.5			X	X	X		
Sequence IIB	13.0 13.0 16.5	ASTM STP 315D, 315E	X					CC, SD, SE MR-L-2104C, MR-L-46152
Sequence IIC	13.0 13.0 16.5	ASTM STP 315F	X					SE MR-L-2104C, MR-L-46152
Sequence IIB	16.5 16.5	ASTM STP 315D		X	X	X		SD
Sequence IIC	16.5	ASTM STP 315E, F		X	X	X	Thickening	SE, MR-L-46152
Sequence IV	Not controlled	ASTM STP 315, 315A, B, C, D				X		SB, SC, SD
Sequence V	9.5 15.5 15.5	ASTM STP 315, 315A, B		X	X			SC
Sequence VB	9.5 15.5 15.5	ASTM STP 315C, D		X	X		PCV valve clogging	SD
Sequence VC		ASTM STP 315E, F		X	X		PCV valve clogging	SE MR-L-2104C, MR-L-46152
Falcon	Max. Vac 15.5	Ford Motor Co. FTM BJ 11-2	X					SD

warped valves.

A variety of antiknocks are currently available and their selection is dependent upon fuel composition, engine design, operating conditions, transmission type used in vehicles, etc. Tetraethyllead has been the principal antiknock, and was the only antiknock used commercially in the U.S. until 1959. In 1959 a manganese antiknock (methylcyclopentadienyl manganese tricarbonyl) was introduced either as a synergist or supplementary antiknock agent for TEL or as an antiknock to be used alone. In 1960 a more volatile lead antiknock (tetramethyllead) entered the antiknock market. Today in addition to TEL and TML, there are chemical mixtures of them (mixed lead alkyls) and physical mixtures of TEL and TML available commercially.

In the recent past the variety of cars to be satisfied has become greater than ever before, ranging from high performance, automatic transmission models to compact and foreign models with manual transmissions. During the same period the introduction of new refining methods has created a wider range of available hydrocarbons for use in gasoline blending. The availability of a number of antiknocks enables refineries to tailor blend a selected antiknock compound and their particular hydrocarbon components into finished gasolines satisfying the greatest proportion of their customer's vehicles at the least possible cost. Each refiner must determine which antiknock offers him the greatest road octane gain at the least cost in his particular gasoline blend. Road octane ratings of gasolines are those found when the gasoline is used in vehicles on the road as contrasted to laboratory octane readings obtained on a standard CFR single-cylinder engine.

Because TML is more volatile than TEL (TML boils at 23°F vs. 350°F for TEL) it reaches the cylinders more readily and follows the gasoline more readily than TEL during rapid engine acceleration. Also because the boiling point of TML is closer to the midrange of commercial gasolines it tends to distribute to the individual cylinder in proportion to the gasoline thereby supplying antiknock quality more uniformly.

Mixed-lead alkyls were introduced to provide a range of antiknocks having both compositions and volatilities intermediate to those of either TEL or TML. The same is true with physical mixtures of TEL and TML. The mixed-lead alkyls are available as triethyl methyllead (MLA 250), diethyl dimethyl lead (MLA 500) and ethyl trimethyl lead (MLA 750). These mixed-lead alkyls are actually equilibrium mixtures of the two basic antiknocks TEL and TML.

The physical mixtures are available in ratios such as 25% TEL and 75% TML, a 50/50 mixture and a 75% TEL and 25% TML.

The various antiknocks and mixtures make available a wide variety of combinations, and again fuel composition largely determines how effective these compounds will be. Specifications for avgas permit use of TEL as an antiknock. Some autogas employs TEL, but unleaded grades have used other materials including ethanol and higher

alcohols as antiknock components.

When a gasoline containing antiknock alone is burned in a spark-ignition engine, it produces non-volatile combustion products. Therefore, commercial antiknock fluids contain scavenging agents - combinations of ethylene dibromide and ethylene dichloride and in the case of aviation gasoline, ethylene dibromide alone. These transform the combustion products of the antiknock into forms that vaporize readily from hot engine surfaces. Scavengers are included as a part of any antiknock compound containing lead.

Earliest antiknock compound formulations were based on use of ethylene dibromide as the scavenger. Interest in the use of ethylene dichloride as a scavenger developed when it appeared the world supply of bromide was being used at a rapid rate. It was determined through extensive automotive testing that a combination of EDB and EDC was actually better on a cost performance basis than EDB alone. The change to a mixture of EDB and EDC occurred in the 1930's for automotive gasolines. At that time ethylene dibromide was specified for aviation gasoline and it has continued to be the scavenger in avgas since it is more effective under sustained high load operation.

An antiknock compound based on methyl cyclopentadienyl manganese tricarbonyl (MMT) has found use in some applications as a complimentary antiknock which promotes the antiknock value of TEL. Adding a very small amount of this manganese compound to leaded gasoline provides a synergetic (greater than proportional) gain in octane numbers. An antiknock compound mixture, Motor 33 Mix, sold by the Ethyl Corporation uses a small amount of MMT along with TEL.

MMT can also be used as a primary antiknock compound to increase octane rating of gasoline when lead is not desired. It is used in small concentrations and can produce up to 4 octane numbers improvement at a concentration of only 0.25 grams per gallon. The octane improvement depends on gasoline hydrocarbon composition, working best in highly paraffinic gasolines. MMT has never been used in avgas and is no longer used in autogas for emission control reasons, at least in the unleaded grades.

DEPOSIT MODIFIERS. Deposit modifiers combat surface ignition and spark plug fouling by altering the chemical characteristics of combustion chamber deposits.

Phosphorous compounds are widely used as deposit modifiers. These additives suppress surface ignition by raising the temperature required to initiate glowing of deposits and by reducing the rate of heat release from oxidation of deposits. Phosphorous compounds are limited in unleaded autogas since phosphorous deteriorates the efficiency of catalytic converters. They are not used in avgas.

SURFACE IGNITION. Surface ignition or deposit ignition occurs when the fuel/air charge is ignited by hot spots within the combustion chamber, most of the time from glowing deposits. To the motorist surface ignition usually causes a sporadic

high frequency knocking called "wild ping" or a low frequency noise, similar to that produced by bad main bearings, called rumble. Wild ping results when the surface ignited flame front causes the pressure and temperature in the unburned portion of the fuel/air charge to rise much faster than in normal combustion. Consequently, the unburned fuel/air mixture is stressed far beyond its antiknock quality and knock results. Rumble on the other hand, is a form of non-knocking combustion. It occurs when ignition from a number of sources produces a very rapid pressure rise and high-peak pressures during the combustion (34).

In extreme cases, surface ignition can heat deposits or engine parts to a point where ignition occurs progressively earlier (preignition) in the cycle. Such runaway preignition can burn holes in pistons or seriously damage exhaust valves and faces within minutes.

Spark plug fouling is covered in some detail in another section of this report, but it is mentioned here because the same compounds which are effective in suppressing surface ignition and rumble are also effective in reducing spark plug fouling. Reference 23 discusses performance of specific alkyl and aryl phosphorous compounds which are effective in alleviating surface ignition and spark plug fouling, and have been used extensively commercially.

ANTIOXIDANTS. Antioxidants are added to gasoline to provide storage stability (retard the formation of gum and precipitates) by delaying the oxidation of both reactive hydrocarbons in commercial gasolines and other materials, such as lead alkyl antiknocks and manganese compounds that may have been added to the gasoline. There are many variables which affect the length of time that gasoline can be stored without unacceptable deterioration. Variables such as crude source, olefinic content, sulphur content, and additive treatment can all influence the storage stability of gasoline. Other factors such as climatic conditions and the type of storage facility can also affect storage life. Antioxidants and metal deactivators are widely used to protect against gum and peroxides produced by oxidation and the precipitates from antiknock compounds.

Gums form in gasoline when the unstable hydrocarbons combined with oxygen (oxidize) or polymerize with each other. Gum formation, in addition to the variables mentioned above, can be influenced by storage temperature, extent to which air is present, and length of storage. When gum is formed it produces a varnish-like deposit that tends to coat and clog fuel lines, carburetor jets, and intake manifolds, and may cause intake valves to stick. In severe cases it can increase exhaust system deposits significantly. High concentrations of gums can increase combustion chamber deposits (35) to an extent that there will be an increase in octane requirement due to these deposits.

In many cases the stability of gasoline can be improved by various refining treatments but more often than not, it is economical to use an antioxidant to accomplish the same purpose.

The insoluble precipitate that can form when a lead antiknock decomposes is promoted by the presence of trace amounts of copper or peroxide in the gasoline. In addition to loss of octane quality, one consequence of the insoluble precipitate is the possibility of fuel line filter plugging. The same antioxidant which protects the gasoline itself is also effective in preventing the decomposition of lead antiknocks. When antiknock decomposition does occur, only a small fraction is involved even though there appears to be a rather large bulk of precipitate.

Many gasoline antioxidants are available. The most common are alkylated phenols and amines. In recent years there has been a trend toward the use of alkylated phenols and reduced use of phenylene diamine types. This has been due to a gradual change in gasoline composition (lower olefin content) and increase in use of catalytic desulphurization processes which tend to eliminate the need for inhibitors or inhibitor sweetening. Amine type inhibitors permit inhibitor sweetening whereas the phenols do not. These developments have also produced a situation where the concentration of antioxidants in autogas has been reduced to values considered to be a bare minimum for protection against decomposition of the lead antiknocks for it is not expected that autogas will be stored for prolonged periods of time.

METAL DEACTIVATORS. It is known that only trace quantities of many metals will catalyze the oxidation of gasoline. Of the several metals having this property, copper is by far the most important. Trace quantities of copper can get into fuel systems by way of some sweetening processes and from contact of refinery streams with brass fittings, copper lines and numerous copper-containing alloys. The presence of as little as 0.1 ppm of soluble copper can have a considerable effect on gasoline stability. In fact, the effect can be so great that even the most effective antioxidants cannot provide adequate stability by themselves. Additives have been found that will effectively destroy the catalytic activity of the dissolved metal. These additives are referred to as metal deactivators and they function by formation of a stable chelate. In this form the copper is inactivated and has no catalytic effect on oxidation. The use of metal deactivators in conjunction with antioxidants will frequently provide the most effective and economical way of stabilizing the gasoline. At the present time the metal deactivator used most extensively is N, N'-disalicylidene-2-diaminopropane. Metal deactivators are not used in avgas because of extreme care in manufacture to guard against contaminant metal (41).

ANTIRUST AGENTS. Rusting can be a problem in fuel systems and in tanks, pipelines, and tankers used to bring the gasoline to the motorist. It is not only costly to the petroleum transportation people, but can cause the motorist trouble in the form of leaky gas tanks, plugged gasoline filters, faulty carburetion, etc. In recent years the automobile carburetor has become more complex, making it more critical to dirt and requiring finer gasoline filters. Rust particles lodging in the needle valve or jets of a carburetor can cause problems such as flooding or float bowl overflow, thus causing malfunction and a dangerous situation.

Rusting is promoted by water which can enter the car and/or gasoline transportation and storage system by condensation or gross contamination. Sea water is particularly harmful and is a constant problem where gasoline is transported by sea. It is difficult to keep water out of a gasoline system even though considerable effort is made to keep the systems dry. Consequently most gasolines contain considerable water which often forms a separate layer on tank bottoms.

Several types of hydrocarbon soluble compounds are used as rust inhibitors. Most gasolines including avgas contain them and these inhibitors are often put in the gasoline at the refinery. Compounds which can impart antirust properties to a gasoline include various fatty amines, sulfonates, alkyl phosphates, and amine phosphates. Several of these compounds, including the fatty amine, not only inhibit rust but have antiicing and carburetor detergency properties. Most of the above additives act by coating metal surfaces with a very thin protective film which keeps water from contacting these surfaces. The fatty amines impart good surface active properties to gasoline and thus reduce carburetor icing, icing in fuel lines and build up of carburetor deposits.

ANTIICING AGENTS. Ice can interfere with engine operation either by plugging fuel lines or by upsetting carburetion. Fuel lines can be plugged by ice crystals present in the fuel. Carburetor icing however is caused by freezing of the water vapor in the air which the engine inducts. The vaporization of gasoline in the carburetor venturi cools the adjacent parts during the period while the engine is warming up. These parts, under some atmospheric conditions, can become cool enough to condense water from the incoming moist air and form ice in the carburetor. When sufficient ice has accumulated at the throttle plate, stalling of the engine during idle can occur. Ice buildup in the venturi can reduce power under high load conditions. The most critical conditions are ambient temperatures of about 40°F and relative humidity of above 60% (23).

It has been shown that the throttle plate temperature in ambient conditions of about 40°F, 100 humidity, will decrease to a value in the neighborhood of 5-7°F, and can accumulate large quantities of ice which tend to cut off the air supply to the engine when the throttle is closed. Usually this condition will persist until the engine and intake system have fully warmed up. Figure 16 shows some test results and the influence of fuel volatility. High volatility promotes icing.

Another type of carburetor icing referred to as "running icing" or turnpike icing is a build up of ice in the carburetor venturi and this tends to act as a choke and cause considerable loss of power and fuel economy due to rich mixtures.

There are two types of carburetor antiicing additives: freeze point depressants and the surface active agents. Freeze point depressants act as antifreezes and are generally of the alcohol or glycol-type materials. Surface active agents are described in the paragraphs above.

Some freeze point depressants and to a lesser extent, the surface active agents are also effective in preventing ice plugging of fuel lines. Some surface active agents have been used specifically for the purpose of preventing this class of problem. It has been suggested that the surfactants act by coating the ice particles and carburetor walls so that they will not cling together or agglomerate. Thus the tiny particles proceed through the intake system unimpeded. Antiicers are not regularly used in avgas. Some experimental antiicers have been developed for avgas however.

DETERGENTS. Basically two classes of detergents are used in autogas. One is designed primarily for keeping carburetors clean or cleaning up dirty carburetors and the other is commonly referred to as the extended type. The most common detergent used is the one for keeping the carburetor clean.

The detergent designed for carburetors alone functions because it prevents the accumulation of or causes the removal of carburetor deposits in the throttle body area. Such deposits are formed mostly during idle operation and arise from airborne contaminants drawn into the carburetor, and deposited on the inside surface of the throttle body just below the throttle plate. These deposits interfere with the air flow past the edge of the throttle plate and richen the air-fuel ratio during low speed and light-load operation. This produces rough idle, frequent stalls, and reduced performance and economy. These deposits by virtue of causing the carburetor to run richer also increase unburned hydrocarbons and carbon monoxide emissions. Use of detergents reduces the need for carburetor adjustment. The effectiveness of these detergents stem from their surface active properties. Such detergents include amines and alkyl amine phosphates.

Detergents referred to commonly as the extended range type are designed to not only clean carburetors, but also the underhead area of the intake valves, intake ports, and in some cases, positive crankcase ventilator. Detergents are not used in avgas because the periodic overhaul eliminates the need for them since critical parts are cleaned at that time.

UPPER CYLINDER LUBRICANTS. Some refineries use light lubricants as gasoline additives to help lubricate cylinders and top piston rings, to reduce valve and ring sticking, and to reduce intake system deposits. These upper cylinder lubricants are usually light mineral oil or low viscosity naphthenic distillates. In some cases they are compounded so as to provide some detergency in the engine crankcase. These oils tend to remain liquid in the intake system thereby keeping the contaminants in solution or in suspension so that they wash through. Not all gasolines contain upper cylinder lubricants. Such oil addition is suspected to cause octane requirement increase and consequently its use has been limited. They are not used in avgas.

DYES. Dyes are added to all gasolines for a number of reasons including indicating the presence of lead antiknocks, to promote sales appeal, to identify various makes or grades of gasoline and to conform with the laws of some states which



require that fuels used for off-highway purposes have a different and distinct color. Gasoline dyes are hydrocarbon soluble organic compounds. Concentrations in gasoline depend on the intensity of the color desired to meet a color standard (this is influenced by the color of the base gasoline).

Most unleaded gasolines require a dye to produce a water-white appearance. The selection of blending compounds for unleaded gasoline is the determining factor whether the dye is needed or not. Dyes are required in avgas.

OXGENATED FUEL BLENDING AGENTS. Over the years there has been much time and effort expended in the possible use of several of the alcohols for automotive and aircraft purposes. Both ethanol and methanol have good antiknock properties and they are in the gasoline boiling range. Use of alcohol as fuels or as blending agents in fuels has occurred to a very limited extent, mostly because of cost performance or problems associated with their use. It is believed there has been greater use of alcohols in foreign countries than in the U.S. In most cases, use in foreign countries was legislated, usually because of an excess of raw materials for making the alcohol or an excess of alcohol itself.

The use of alcohols in aviation gasolines in the past has generally been limited to injection of blends of water-alcohol during take-off to increase knock-limited power. Water-alcohol injection provided cooling in the combustion chamber and the alcohol provided some antiknock quality. These were generally not used during cruise conditions. The quantity of water-alcohol blend was limited to that needed for take-off and climb.

The alcohols are hygroscopic and have an affinity for water with methanol more hygroscopic than ethanol. This has been one of the main drawbacks associated with the use of alcohol in automotive service. In the past it has been found that alcohol, in particular methanol, was prone to preignite and in some cases could cause serious preignition.

Another major problem associated with methanol-gasoline blends is corrosion of the ternplate lining of the vehicle fuel system and attack by methanol of magnesium and some aluminum. Methanol and ethanol have an effect on many of the elastomers used in the current passenger car. A common problem is increased swelling of gaskets and seal materials compared with gasoline alone and deterioration of cellular foam floats.

In recent years because of the energy problem and high cost of crude there has been considerable interest in use of ethyl alcohol in autogas to conserve energy. Ethanol is now being widely used in Gasohol - a term copyrighted by the state of Nebraska for 10 vol.% alcohol plus 90 vol.% unleaded gasoline.

In the absence of recalibration of the carburetor, alcohols tend to lean out mixtures, causing engine roughness. Starting and warm-up characteristics are deteriorated in the winter and possible vapor lock is enhanced in the summer.

Ethanol and water are miscible in all proportions and dry ethanol and gasoline are likewise miscible. On the other hand, gasoline and water are essentially immiscible. A mixture of alcohol, gasoline and water can remain as a mixture in relatively narrow limits of composition. Outside of these limits, separation occurs. Without going into technical details this can cause problems because the alcohol and water tend to go to the bottom and gasoline will remain at the top. In a large storage container and without mechanical mixing, engines receiving the top phase with considerably different volatility and stoichiometry than the bottom phase, could run rather poorly. If such blends were used in aircraft, the volatility and stoichiometry could be significantly different than current avgas for which the aircraft was designed.

The potential problems of poor engine performance and fuel system deterioration tend to preclude consideration of any autogas blended with ethanol or methanol to a level more than about 5%. These problems are solvable but extensive research on materials is required.

In addition to methanol and ethanol mentioned above, there are some recent developments in other oxygenates. Getting special attention are: 1) tertiarybutyl alcohol, or t-butyl alcohol or t-butanol (TBA) and 2) 2-methyl,2-butyl ether (MTBE) (19).

TBA has been used in this country for a number of years by companies who produce it in large volume as a byproduct from acetone manufacture. They blend it into gasoline as a convenient way of disposing of a chemical which is in over supply. MTBE has been manufactured and used in gasoline in Italy and Germany for some time. Manufacture has now begun in the United States.

EPA has approved the use of 50/50 methanol/t-butanol, t-butanol alone, and MTBE up to 7 volume %, and ethanol up to 10% volume.

A review of the antiknock characteristics of the oxygenates would lead one to believe there is much incentive to use them for antiknock purposes. With increasing use of unleaded gasoline, there is considerable competition for the high octane unleaded gasoline components such as alkylate and reformates. Some of the alcohols have drawbacks that are inescapable. MTBE shows considerable promise even though methanol is used in its manufacture. MTBE does not produce any problems when blended into gasoline and alcohol at the 7% level.

The distillation curve of mixtures of gasoline and alcohol have a rather unusual shape because alcohols and hydrocarbons form azeotropic mixtures, or lower boiling mixtures than would be expected from their individual boiling points. Thus, essentially all the alcohols are removed at the midpoint and the balance of the curve is nearly the same as for gasoline alone. Reid pressures and V/L ratios are greatly increased.

MTBE does not form azeotropic mixtures with hydrocarbons. The distillation curve of a mixture tends to follow that of a normal gasoline. This is true notwithstanding

ing the fact MTBE has a lower boiling point than that of either methanol or ethanol. This means that MTBE distills throughout the boiling range of the gasoline.

Water separation is not a problem with either t-butanol or MTBE. These larger molecules have a greater ratio of organic carbon atoms and are less soluble in water.

In summary, the use of oxygenates in autogas has been increasing. This further complicates consideration of autogas as a substitute for avgas. Information is needed on any harmful effects of these fuel additives in aircraft fuel systems. At present there is no reliable information related to aircraft fuel system performance and thus any positive recommendation with respect to such blending agents is not possible at this time.

#### SUMMARY

In the preceding sections several problems were discussed associated with matching gasoline fuels to engines. Much information is available for automotive systems and relatively little for aircraft. Table 9 summarizes the problems discussed and indicates differences between avgas and autogas and the nature of the problem. In terms of antiknock quality, all autogases meet the lean requirement of Grade 80/87 avgas and probably meet the rich requirement as well, but this cannot be proven at this time. Autogas antiknock quality is far too low to satisfy the higher avgas grades. In one problem area only is there a large difference between avgas and autogas, that is vapor lock. With the exception of icing the other problems are relatively moderate and may be circumvented by more frequent maintenance including oil changes.

Filter and fuel line freezing problems can be alleviated by the addition of anti-icers and by careful draining of tank bottoms. Carburetor icing can be controlled by suitable air preheating, a common practice on modern automobiles.

The vapor lock problem is most difficult to solve. In terms of fuel metering two possibilities present themselves. One is to fully and continuously evaporate the fuel prior to metering and thus entirely circumvent the problem associated with metering evaporating fluids. For this, a separate system is required for starting and warm up until exhaust heat is available for vaporization. The other possibility is to employ high pressure individual cylinder fuel injection or single point injection above the throttle body. In this way, solid fuel is metered and the large pressure drop at the nozzle assures that liquid fuel is in the lines. One advantage of single point injection is that the injector is removed from the hot intake port. Continuous recirculation of the fuel back to the tank can be used to keep injectors cool and vapor return to the fuel tank used to eliminate injector vapor problems. Some invention and development is required to provide entirely

TABLE 9. PROBLEM SEVERITY COMPARISON

<u>Problem</u>	<u>Severity Difference Between Autogas and Avgas</u>	<u>Suddenness of Onset</u>
<u>Immediate or Short Range</u>		
Knock	Little	Rapid
Preignition	Moderate (worse)	Very rapid
Deposit ignition	Moderate (worse)	Rapid
Vapor lock	Large (worse)	Rapid
Icing - carburetor - filters & lines	Moderate (worse) Moderate (worse)	Rapid Rapid
Cold start	Moderate (better)	Rapid
Hot restart	Moderate (worse)	Rapid
Spark plug	Moderate (better with unleaded) (worse with leaded)	Rapid
Fuel safety	Little	Rapid
<u>Long Term</u>		
Drivability (maldistribution)	Moderate (worse)	Continuous
Valve sticking and wear	Moderate (worse)	Very gradual
Compatibility with materials and corrosion	Moderate (worse)	Very gradual
Lubrication and wear	Moderate (worse)	Very gradual
Storage instability	Moderate (worse)	Rapid

adquate systems of either type.

The vapor lock problems associated with fuel line and pump volume can be alleviated by a combination of:

- a. larger diameter lines
- b. in-tank pump
- c. routing of lines for minimum heat pick-up

Centrifugal in-tank pumps have good potential for minimal suction pressure drop, high pressure and high flow. Perhaps more than one stage is required depending on pressure requirements or two pumps in series of different design.

By employing advanced technology, future aircraft may be built to be insensitive to the widely varying properties of autogas, properties whose variations appear to be increasing as refiners attempt to improve refinery efficiency. The use of oxygenates as supplements in autogas opens up a new degree of autogas variation and is likely to introduce severe material problems both in automobiles and aircraft whose materials have not been selected for use with these blending agents initially.

Use of automotive oils with their greater capability for neutralizing acids and their improved detergent and dispersant properties could alleviate problems produced by increased sulfur and higher volumes of high boiling point constituents in autogas. However, the high blowby and oil consumption rates of aircraft engines must be reduced through improved design to minimize oil contamination and to minimize combustion chamber deposits from the ash-forming additives of automotive oils. A Wankel engine has an advantage in this regard in that the lubricating oil is isolated from the blowby.

In order to provide a basis for change it may be desirable to design a standard fuel system certification test. Such a test may be similar in concept to the ASTM Sequence Test for automotive lubricants, but rather employ standard lubricants and standard test fuels representative of the extremes of expected autogas properties and composition. Engines and fuel systems thought to be most sensitive would be used as test beds. Obviously considerable effort will be required to design appropriate tests, but in the absence of established procedures as a baseline, it will be difficult if not impossible to effect any change in the status quo.

## REFERENCES

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APPENDIX A

TABLE A-1. REGULAR AUTOGAS DATA (REF. 11) SUMMER, 1979

DISTRICT NO. AND NAME	NO. OF BRANDS	NO. OF SAMPLES		A.P.I. GRAVITY ASTM D 157	SULFUR ASTM D 1266 WT. %	GUM ASTM D 381 MG	BENZENE ASTM D 3606 VOL. %	LEAD G/GAL	OCTANE NUMBER		
									RESEARCH, ASTM D 2699	MOTOR, ASTM D 2700	AA-1 1
1 NORTHEAST	11	21	MAX.	65.8	0.060	3	1.70	3.32	93.7	88.0	90.6
			Avg.	61.6	0.098	2	1.80	2.41	93.0	86.8	89.7
			MIN.	57.5	0.030	1	1.10	1.79	91.8	85.0	88.9
2 MID-ATLANTIC EAST	17	130	MAX.	71.3	0.107	4	1.60	3.40	96.4	89.0	91.8
			Avg.	61.2	0.034	1	0.87	2.31	93.0	86.3	89.7
			MIN.	57.8	0.002	0	0.10	0.83	91.0	84.0	87.6
3 SOUTHEAST	18	104	MAX.	65.0	0.070	2	1.70	3.25	96.2	88.9	91.5
			Avg.	61.5	0.030	1	1.45	2.90	93.1	86.1	89.7
			MIN.	56.8	0.030	0	1.10	1.41	91.5	82.4	87.2
4 APPALACHIAN	14	71	MAX.	64.4	0.080	5	1.11	3.46	99.5	91.4	93.5
			Avg.	61.0	0.026	1	0.79	1.74	93.1	86.0	89.6
			MIN.	57.4	0.011	0	0.37	0.47	90.9	84.0	88.5
5 MICHIGAN	13	41	MAX.	65.0	0.140	4	2.60	3.01	94.3	86.8	89.9
			Avg.	61.3	0.058	2	1.00	1.73	93.1	85.7	89.4
			MIN.	57.9	0.010	0	0.40	0.64	92.0	84.1	88.8
6 NORTH ILLINOIS	11	29	MAX.	63.4	—	3	—	2.14	94.0	87.4	90.0
			Avg.	61.2	—	1	—	1.88	92.9	85.9	89.4
			MIN.	58.4	—	0	—	1.08	91.8	84.7	88.3
7 CENTRAL MISSISSIPPI	14	32	MAX.	63.8	0.111	5	1.30	4.14	94.8	87.1	90.6
			Avg.	61.4	0.080	2	1.18	2.41	93.2	86.0	89.6
			MIN.	58.1	0.028	1	0.41	1.25	91.8	84.6	88.6
8 LOWER MISSISSIPPI	15	45	MAX.	66.0	0.070	1	1.60	4.06	94.4	87.7	90.9
			Avg.	61.5	0.070	0	1.60	2.27	92.8	86.3	89.6
			MIN.	57.8	0.070	0	1.60	0.49	91.0	85.0	88.7
9 NORTH PLAINS	11	12	MAX.	64.2	0.019	1	0.33	3.10	93.0	86.0	89.2
			Avg.	61.9	0.019	1	0.33	1.93	92.3	85.3	88.8
			MIN.	59.9	0.019	1	0.33	1.11	91.6	84.6	88.3
10 CENTRAL PLAINS	12	45	MAX.	64.9	0.080	4	3.00	3.68	94.4	87.1	90.3
			Avg.	61.2	0.034	2	1.17	2.11	92.3	85.3	89.6
			MIN.	55.5	0.019	0	0.30	0.78	88.3	82.5	86.8
11 SOUTH PLAINS	22	64	MAX.	67.8	0.030	3	1.70	3.40	94.3	88.7	90.7
			Avg.	61.2	0.027	1	1.00	2.05	92.7	85.3	89.1
			MIN.	56.6	0.010	0	0.60	0.86	91.0	84.4	87.9
12 SOUTH TEXAS	12	38	MAX.	65.9	0.030	2	1.10	3.41	95.3	88.6	90.9
			Avg.	61.0	0.030	1	1.10	2.19	93.1	86.2	89.7
			MIN.	53.8	0.010	0	1.10	1.26	91.8	85.2	89.0
13 SOUTH MOUNTAIN STATES	14	155	MAX.	66.8	0.058	3	2.44	4.22	96.6	88.7	92.7
			Avg.	60.9	0.017	1	1.37	1.59	92.1	84.9	88.3
			MIN.	53.5	0.005	0	0.70	0.52	89.0	81.0	86.0
14 NORTH MOUNTAIN STATES	12	66	MAX.	66.2	0.146	2	0.61	1.56	93.5	86.0	89.3
			Avg.	60.8	0.044	1	0.61	1.02	91.5	84.3	87.9
			MIN.	58.0	0.027	0	0.61	0.60	88.3	80.9	85.0
15 PACIFIC NORTHWEST	7	23	MAX.	62.8	0.109	2	1.76	2.90	94.1	87.7	89.8
			Avg.	59.7	0.100	2	1.25	1.66	92.6	85.7	89.2
			MIN.	57.9	0.010	2	0.70	0.77	91.2	84.6	88.2
16 NORTH CALIFORNIA	9	35	MAX.	61.1	0.229	4	1.90	1.46	95.4	86.9	90.3
			Avg.	56.8	0.087	2	1.44	0.92	93.9	85.2	89.6
			MIN.	54.7	0.010	0	1.09	0.59	92.7	83.7	89.0
17 SOUTH CALIFORNIA	10	40	MAX.	61.0	0.099	2	1.90	2.69	94.8	86.0	90.3
			Avg.	57.5	0.189	1	1.02	1.16	93.4	85.1	89.3
			MIN.	50.7	0.010	0	0.26	0.24	87.7	83.2	86.6

A-1

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TABLE A-1. REGULAR AUTOGAS DATA (REF. 11) SUMMER, 1979 (Continued)

R.V.P. ASTM D 323 lb	20 V/L ASTM D 439 °F	DISTILLATION, ASTM D 86										END POINT	RESIDUAL %	LOSS %
		TEMPERATURE, °F (CORRECTED TO 760 MM HG)												
		INITIAL BOILING PT.	PERCENT EVAPORATED											
			5	10	20	30	50	70	90	95				
11.8 10.5 9.4	129 129 123	86	102	114	136	158	204	265	341	368	407	0.8	1.4	
11.8 10.2 8.9	141 131 121	88	103	115	138	160	210	266	345	378	417	1.0	1.6	
11.3 9.7 8.7	143 133 125	89	105	118	139	160	210	269	346	380	415	0.9	1.5	
11.6 10.7 8.5	142 130 123	87	102	116	137	160	209	264	344	376	421	0.8	2.2	
11.7 10.9 9.8	138 128 121	86	101	115	136	158	207	267	353	392	419	1.3	1.7	
12.0 10.7 8.7	137 128 124	85	102	116	136	157	204	262	349	390	428	1.5	1.4	
12.5 10.7 8.1	144 130 117	88	103	117	137	159	208	259	335	369	413	0.8	1.8	
10.8 9.5 8.2	140 134 128	90	106	118	138	158	204	257	334	367	411	1.2	1.6	
10.5 10.5 10.5	126 126 126	72	—	114	130	146	189	250	340	—	410	0.5	2.5	
10.1 9.1 7.8	145 136 131	90	107	120	141	161	204	267	332	366	409	0.8	1.3	
10.7 9.5 8.1	141 132 124	91	107	119	139	160	208	264	340	373	412	0.8	1.4	
10.3 9.0 7.6	146 136 126	91	107	119	138	159	207	269	348	379	413	0.9	1.0	
9.7 8.3 6.9	158 143 128	95	111	127	148	169	213	263	337	371	414	0.9	1.5	
11.0 9.3 6.9	153 137 124	95	108	122	144	166	211	259	338	375	412	1.0	2.8	
11.7 9.1 8.2	141 132 125	87	102	114	136	160	209	268	347	388	416	1.1	2.1	
8.6 8.1 7.9	153 147 140	96	113	131	154	177	223	274	343	372	415	1.0	1.3	
8.9 8.2 4.8	177 143 133	96	116	128	146	166	215	273	343	374	415	1.0	1.2	

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TABLE A-2. PREMIUM AUTOGAS DATA (REF. 11) SUMMER, 1979

DISTRICT NO. AND NAME	NO. OF BRANDS	NO. OF SAMPLES		A. P. I. GRAVITY ASTM D 1287	SULFUR ASTM D 1266 WT. %	PHM ASTM D 381 MO	METHANE ASTM D 306 VOL. %	LEAD G/GAL	OCTANE NUMBER		
									RESEARCH ASTM D 2699	MOTOR ASTM D 2700	R+M 2
1 NORTH EAST	5	5	MAX. AVE. MIN.	65.7 61.8 59.5	— — —	— — —	— — —	3.67 2.81 2.04	98.5 98.0 97.8	90.8 90.0 89.0	94.4 94.0 93.4
2 MID-ATLANTIC COAST	17	68	MAX. AVE. MIN.	65.1 60.6 54.9	0.069 0.021 0.002	4 1 0	1.94 0.69 0.30	4.17 2.39 0.01	99.0 97.9 96.4	91.7 89.7 85.6	95.2 93.8 91.5
3 SOUTH EAST	14	45	MAX. AVE. MIN.	63.2 60.2 56.4	— — —	1 0 0	— — —	3.71 2.76 1.60	99.8 98.0 96.6	91.4 90.0 87.0	95.1 94.0 92.5
4 APPALACHIAN	9	27	MAX. AVE. MIN.	66.0 60.3 57.0	0.041 0.021 0.003	5 2 0	1.21 0.63 0.20	3.60 2.32 1.79	99.8 97.3 96.5	91.2 90.3 89.1	95.2 94.0 93.3
5 MICHIGAN	5	7	MAX. AVE. MIN.	69.1 61.9 58.9	0.030 0.038 0.026	1 1 0	0.30 0.42 0.34	3.22 2.36 1.65	98.7 98.0 97.4	90.2 89.8 88.8	94.3 93.9 93.2
6 NORTH ILLINOIS	3	4	MAX. AVE. MIN.	64.0 61.7 60.4	— — —	1 2 1	— — —	2.08 2.08 1.99	97.3 96.9 96.2	90.7 89.7 89.1	94.0 93.4 92.7
7 CENTRAL MISSISSIPPI	10	17	MAX. AVE. MIN.	63.1 59.1 56.9	0.072 0.031 0.012	6 3 1	1.56 1.09 0.62	3.42 1.92 0.00	98.8 97.8 97.0	91.0 89.3 87.0	94.4 93.6 92.4
8 LOWER MISSISSIPPI	9	15	MAX. AVE. MIN.	63.9 60.3 55.6	— — —	1 1 0	— — —	3.75 2.68 1.30	98.5 97.7 96.7	91.0 90.0 86.6	94.5 93.9 91.9
9 NORTH PLAINS	1	1	MAX. AVE. MIN.	61.1 61.1 61.1	0.013 0.013 0.013	1 1 1	0.67 0.67 0.67	3.80 3.80 3.80	98.4 98.4 98.4	91.0 91.0 91.0	94.7 94.7 94.7
10 CENTRAL PLAINS	5	12	MAX. AVE. MIN.	64.3 64.3 59.3	0.060 0.035 0.018	1 1 0	0.60 0.40 0.20	2.86 2.22 1.00	99.2 97.8 96.3	92.2 90.6 87.8	95.3 94.2 92.7
11 SOUTHWEST PLAINS	14	28	MAX. AVE. MIN.	65.6 61.4 56.0	0.030 0.023 0.020	4 1 0	1.30 0.91 0.51	3.23 2.34 1.60	99.3 98.5 96.4	93.0 90.7 87.5	95.3 94.6 93.1
12 SOUTH TEXAS	6	0	MAX. AVE. MIN.	61.3 60.4 58.0	— — —	1 1 0	— — —	3.34 2.20 1.25	99.3 98.2 97.4	90.7 89.8 88.6	94.4 94.1 93.7
13 SOUTH MOUNTAIN STATES	18	81	MAX. AVE. MIN.	68.0 60.9 53.8	0.395 0.333 0.006	4 1 0	1.67 1.13 0.63	4.64 2.13 0.63	99.8 96.8 93.6	93.8 89.1 86.0	96.2 93.0 90.3
14 NORTH MOUNTAIN STATES	12	39	MAX. AVE. MIN.	68.6 64.5 62.0	0.128 0.066 0.023	2 1 0	0.33 0.33 0.33	2.21 1.43 0.75	99.8 96.9 93.1	92.1 89.3 84.0	96.0 93.1 89.6
15 PACIFIC NORTHWEST	8	26	MAX. AVE. MIN.	63.3 59.9 57.6	0.149 0.060 0.006	2 2 2	2.01 1.40 0.88	2.70 1.58 0.74	98.1 97.1 96.0	91.3 89.2 87.7	93.9 93.2 92.5
16 NORTH CALIFORNIA	18	30	MAX. AVE. MIN.	59.5 56.3 52.8	0.192 0.060 0.002	3 2 1	2.40 1.69 1.30	2.97 1.36 0.47	98.5 97.4 96.0	90.0 88.8 87.3	93.8 93.1 92.4
17 SOUTH CALIFORNIA	9	31	MAX. AVE. MIN.	61.4 58.3 53.8	0.474 0.101 0.010	3 1 0	1.50 1.10 0.71	2.70 1.59 0.70	98.6 97.0 95.9	89.7 88.7 87.6	93.7 92.9 92.1

TABLE A-2. PREMIUM AUTOGAS DATA (REF. 11) SUMMER, 1979 (Continued)

R.V.P. ASTM D 323 PSI.	20 V/L ASTM D 439 °F	DISTILLATION, ASTM D 86										END POINT	RESIDUAL %	LOSS %
		TEMPERATURE, °F (CORRECTED TO 760 MM Hg)												
		INITIAL BOILING PT.	PERCENT EVAPORATED											
			5	10	20	30	40	50	60	70	80			
12.1 11.1 10.6	130 128 121	82	98	106	126	149	212	270	334	366	399	0.9	2.3	
12.0 10.4 8.7	139 131 122	87	101	113	136	160	218	269	340	371	411	0.9	1.6	
11.9 10.1 8.7	146 132 125	88	102	115	138	162	216	266	346	374	412	0.9	1.7	
13.1 11.0 9.4	138 127 117	83	96	110	133	159	213	268	342	372	421	0.9	2.5	
13.4 11.3 10.1	132 127 116	80	94	109	133	159	216	271	353	395	433	1.4	2.0	
11.7 11.2 10.6	129 126 125	79	94	110	137	167	211	262	348	390	429	1.2	1.8	
12.2 10.3 7.6	148 133 121	87	104	118	142	168	216	261	331	365	407	0.8	2.1	
11.5 9.9 8.8	141 133 127	88	104	117	138	162	214	262	332	364	405	0.8	1.3	
9.7 9.7 9.7	139 139 139	88	—	129	158	183	224	262	352	—	428	0.8	2.0	
10.8 9.4 8.3	143 135 127	90	106	119	141	165	219	262	329	374	417	0.8	1.3	
11.0 9.9 8.8	145 135 124	89	105	120	146	173	218	268	328	361	408	0.8	1.6	
10.9 10.1 8.7	137 132 129	84	103	114	137	163	215	263	326	368	408	1.0	1.1	
11.0 9.7 8.7	142 142 123	93	109	126	149	172	216	259	322	368	412	0.9	1.7	
13.2 9.9 7.8	147 135 118	93	105	120	148	171	215	254	333	374	413	1.0	3.0	
12.3 10.4 8.8	139 129 116	86	100	113	136	160	208	256	327	361	403	1.0	2.4	
9.3 8.9 7.3	151 144 138	96	116	130	153	175	219	268	334	364	417	1.0	1.2	
9.0 8.5 7.8	148 142 137	92	113	127	149	171	215	264	332	361	414	1.0	1.1	

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TABLE A-3. UNLEADED AUTOGAS DATA (REF. 11) SUMMER, 1979

DISTRICT NO. AND NAME	NO. OF BRANDS	NO. OF SAMPLES		A.P.T. GRAVITY, ASTM D 287	SULFUR, ASTM D 1266 WT. %	GUM ASTM D 381 MG	BENZENE ASTM D 1606 VOL. %	OCTANE NUMBER			R.V.P. ASTM D 323 PSI
								RESEARCH ASTM D 2699	MOTOR ASTM D 2700	$\frac{R+M}{2}$	
1 NORTHEAST	15	32	MAX.	62.1	0.030	3	1.30	99.2	89.1	93.7	12.0
			AVE.	58.1	0.037	2	1.00	93.8	84.2	89.1	10.5
			MIN.	52.5	0.030	1	0.70	91.3	82.4	87.2	9.8
2 MID-ATLANTIC COAST	21	169	MAX.	64.0	0.070	7	2.40	99.3	89.4	93.6	12.4
			AVE.	59.5	0.023	1	0.84	93.5	84.2	88.9	10.2
			MIN.	49.1	0.002	0	0.20	91.4	82.0	86.8	7.0
3 SOUTH EAST	21	98	MAX.	66.3	0.030	3	1.20	99.6	89.2	93.8	10.9
			AVE.	58.5	0.033	1	1.03	93.2	84.3	88.8	9.6
			MIN.	51.8	0.020	0	0.80	90.8	82.3	86.8	8.2
4 APPALACHIAN	17	81	MAX.	64.9	0.036	5	4.30	99.2	87.8	93.2	12.0
			AVE.	59.3	0.017	2	1.02	92.8	84.0	88.4	10.6
			MIN.	52.5	0.000	0	0.19	90.9	82.1	86.7	8.7
5 MICHIGAN	17	52	MAX.	63.8	0.100	5	2.20	98.5	87.7	92.8	12.3
			AVE.	59.6	0.036	1	1.02	92.9	84.4	88.7	10.9
			MIN.	55.9	0.004	0	0.50	91.1	82.9	87.1	8.8
6 NORTH ILLINOIS	13	36	MAX.	63.6	—	2	—	98.3	88.0	93.1	11.9
			AVE.	59.4	—	1	—	93.2	84.5	88.9	10.9
			MIN.	54.1	—	0	—	90.8	82.6	87.0	8.6
7 CENTRAL MISSISSIPPI	17	36	MAX.	66.9	0.109	3	1.39	98.8	87.8	93.1	12.5
			AVE.	58.7	0.041	2	1.17	92.9	83.8	88.4	10.4
			MIN.	54.2	0.025	1	0.87	90.6	81.3	86.6	8.1
8 LOWER MISSISSIPPI	17	49	MAX.	61.8	0.030	1	1.00	99.5	87.8	93.3	10.8
			AVE.	57.4	0.050	1	1.00	93.5	84.2	88.9	9.3
			MIN.	51.1	0.050	1	1.00	90.6	82.0	86.6	8.6
9 NORTH PLAINES	12	14	MAX.	62.9	0.015	1	0.75	97.4	87.2	92.3	9.2
			AVE.	61.0	0.015	1	0.75	92.8	84.2	88.5	9.2
			MIN.	57.2	0.015	1	0.75	91.6	82.6	87.3	9.2
10 CENTRAL PLAINES	14	55	MAX.	66.5	0.090	3	4.00	98.3	87.9	93.0	10.6
			AVE.	60.1	0.036	1	1.10	92.9	84.2	88.5	9.2
			MIN.	48.5	0.010	0	0.20	89.2	82.4	85.9	8.2
11 SOUTH PLAINES	25	66	MAX.	72.0	0.039	4	3.40	97.9	88.0	92.7	11.0
			AVE.	60.6	0.014	1	1.54	92.2	84.1	88.2	9.5
			MIN.	49.1	0.001	0	0.40	90.6	82.3	86.9	8.4
12 SOUTH TEXAS	14	46	MAX.	64.8	0.030	3	1.30	98.5	88.0	92.7	10.6
			AVE.	58.4	0.025	1	1.08	93.6	83.9	88.5	9.4
			MIN.	53.6	0.020	0	0.70	90.8	82.2	86.8	8.4
13 SOUTH MOUNTAIN STATES	20	118	MAX.	64.3	0.496	1	2.64	96.0	87.3	90.6	10.0
			AVE.	59.3	0.248	1	1.24	91.4	83.1	87.3	8.7
			MIN.	50.0	0.018	0	0.67	88.8	80.1	84.6	7.4
14 NORTH MOUNTAIN STATES	13	38	MAX.	68.7	0.087	1	0.19	92.2	86.9	88.5	11.5
			AVE.	61.5	0.028	1	0.19	91.2	82.9	87.0	9.6
			MIN.	54.5	0.019	0	0.19	89.7	81.2	85.8	7.3
PACIFIC NORTHWEST	8	26	MAX.	61.9	0.322	7	2.00	99.0	86.8	90.6	12.2
			AVE.	57.3	0.055	7	1.26	93.1	84.5	88.8	10.3
			MIN.	52.5	0.005	7	0.62	91.6	83.5	87.7	9.1
NORTH CALIFORNIA	11	37	MAX.	57.8	0.137	3	2.30	96.2	86.1	91.0	8.8
			AVE.	54.9	0.037	2	1.62	94.1	84.4	89.3	8.0
			MIN.	52.0	0.010	0	1.10	91.6	82.4	87.0	7.5
SOUTH CALIFORNIA	13	48	MAX.	64.0	0.785	3	2.50	96.2	85.6	90.9	8.9
			AVE.	55.1	0.113	1	1.38	94.3	84.3	89.3	8.4
			MIN.	50.4	0.010	0	0.56	91.5	82.7	87.1	7.7

TABLE A-3. UNLEADED AUTOGAS DATA (REF. 11)  
SUMMER, 1979 (CONTINUED)

20 V/L ASTM D 432 °F	DISTILLATION, ASTM D 86										END POINT	RESIDUAL %	LOSS %
	TEMPERATURE, °F (CORRECTED TO 760 MM Hg)												
	INITIAL BOILING PT	PERCENT EVAPORATED											
		5	10	20	30	50	70	90	95				
129 130 125	85	99	112	133	157	220	271	332	358	400	0.8	1.4	
138 132 119	87	102	115	129	165	222	270	334	364	408	1.0	1.6	
142 134 128	88	104	116	138	163	214	270	335	365	403	0.8	1.3	
142 132 122	86	101	116	142	170	224	274	341	371	422	0.9	2.1	
141 131 123	85	99	117	144	172	223	272	344	380	425	1.3	2.4	
145 131 123	83	99	115	142	171	224	272	342	379	421	1.5	1.8	
145 133 118	87	104	117	143	170	220	269	338	371	412	0.9	1.7	
141 137 128	88	101	119	144	171	223	271	336	363	406	0.9	1.5	
143 143 143	89	—	136	154	191	231	275	373	—	434	0.5	4.5	
146 137 127	91	105	119	142	168	214	252	328	362	409	0.8	1.6	
148 137 130	89	106	121	147	174	220	260	329	363	406	0.9	1.3	
143 137 129	91	106	119	141	166	224	268	326	356	396	1.0	1.1	
144 142 133	91	110	125	149	174	222	266	323	368	412	1.0	1.4	
147 135 123	90	105	118	140	166	212	253	325	364	404	0.9	2.6	
148 136 127	88	104	118	149	180	224	269	330	364	405	1.4	2.8	
153 148 140	97	110	133	158	183	228	272	333	361	410	0.9	1.4	
159 146 139	95	116	130	155	181	230	274	331	360	411	0.9	1.2	

TABLE A-4. REGULAR AUTOGAS DATA (REF. 12) WINTER, 1978-79

DISTRICT NO. AND NAME	NO. OF STATIONS	NO. OF SAMPLES		A. S. I. GRAVITY ASTM D 1287	SULFUR ASTM D 1266 WT. %	CUM ASTM D 381 MO	SENEB ASTM D 1606 VOL. %	LEAD G/GAL	OCTANE NUMBER		
									RESEARCH ASTM D 1699	MONROE ASTM D 1708	R&M 2
1 NORTHWEST	11	21	MAX.	68.1	0.050	2	1.00	2.60	94.2	87.7	90.6
			AVE.	63.2	0.050	1	2.50	1.80	93.6	86.6	90.1
			MIN.	61.3	0.050	0	0.80	0.74	92.9	85.7	89.8
2 MID-ATLANTIC COAST	18	140	MAX.	65.2	0.084	2	1.54	2.60	94.4	88.4	92.1
			AVE.	62.9	0.090	1	1.02	2.08	93.6	86.7	90.2
			MIN.	58.9	0.020	1	0.45	0.85	92.7	86.1	89.6
3 SOUTHEAST	19	92	MAX.	63.1	0.070	3	1.50	2.14	94.4	88.0	91.2
			AVE.	62.6	0.061	1	1.35	2.11	93.4	86.4	89.7
			MIN.	61.3	0.081	0	1.20	1.71	93.1	85.1	89.7
4 APPALACHIAN	14	54	MAX.	70.5	0.029	5	1.11	3.70	94.6	87.5	90.2
			AVE.	63.4	0.022	2	1.00	1.61	93.4	86.2	89.8
			MIN.	61.2	0.005	0	0.45	0.85	91.9	85.1	89.8
5 MICHIGAN	13	40	MAX.	64.7	0.128	3	2.00	2.51	93.7	86.6	90.2
			AVE.	62.0	0.045	1	1.01	1.36	93.2	85.9	89.6
			MIN.	59.3	0.020	0	0.50	0.45	92.4	85.1	89.0
6 NORTH ILLINOIS	11	24	MAX.	64.5	0.131	2	2.00	2.64	93.8	86.4	89.9
			AVE.	62.2	0.032	1	1.32	1.81	93.3	85.7	89.6
			MIN.	60.1	0.016	0	0.80	0.78	92.8	84.7	89.3
7 CENTRAL MISSISSIPPI	20	46	MAX.	64.6	0.049	2	1.01	2.35	94.6	88.0	91.0
			AVE.	62.8	0.041	2	0.84	2.45	93.4	86.2	89.8
			MIN.	59.9	0.034	1	0.47	0.90	92.4	84.6	88.7
8 LOWER MISSISSIPPI	15	46	MAX.	64.2	0.050	2	0.90	4.02	94.7	88.8	91.8
			AVE.	62.6	0.030	1	0.90	2.16	93.5	86.7	90.1
			MIN.	58.9	0.030	1	0.90	0.27	92.1	85.1	89.1
9 NORTH PLAINS	11	11	MAX.	64.6	—	—	—	2.53	93.4	86.0	89.7
			AVE.	63.7	—	—	—	1.16	93.0	85.1	89.0
			MIN.	62.4	—	—	—	0.75	92.6	84.7	88.7
10 CENTRAL PLAINS	11	38	MAX.	66.1	—	0	—	2.70	93.5	87.0	90.3
			AVE.	64.3	—	0	—	1.75	92.8	86.1	89.5
			MIN.	60.9	—	0	—	1.23	92.4	85.3	89.1
11 SOUTH PLAINS	23	70	MAX.	67.6	0.090	6	1.15	2.54	94.2	87.2	90.1
			AVE.	63.8	0.054	2	0.81	1.98	92.9	86.1	89.5
			MIN.	60.7	0.036	0	0.31	0.86	92.0	85.3	88.7
12 SOUTH TEXAS	13	38	MAX.	64.3	—	4	—	2.91	94.1	87.1	90.4
			AVE.	62.9	—	1	—	2.16	93.3	86.4	89.9
			MIN.	61.5	—	0	—	1.01	92.7	85.7	89.6
13 SOUTH MOUNTAIN STATES	20	110	MAX.	65.7	0.080	2	1.36	3.70	93.1	85.9	89.2
			AVE.	62.0	0.048	2	1.10	1.73	91.7	85.0	88.4
			MIN.	59.9	0.019	1	0.74	0.70	89.9	83.4	85.7
14 NORTH MOUNTAIN STATES	13	89	MAX.	64.1	0.046	1	—	2.05	93.4	86.1	89.6
			AVE.	61.9	0.039	1	—	1.09	92.6	84.6	88.6
			MIN.	59.8	0.026	1	—	0.45	91.6	83.9	87.8
15 PACIFIC NORTHWEST	8	23	MAX.	61.9	0.049	2	1.84	2.17	93.3	86.8	90.0
			AVE.	61.0	0.031	1	1.46	1.32	93.2	85.8	89.5
			MIN.	60.0	0.006	1	0.73	1.01	92.0	84.9	89.1
16 NORTH CALIFORNIA	10	35	MAX.	61.3	0.032	2	1.85	1.65	94.3	86.3	90.3
			AVE.	59.2	0.018	1	1.47	0.47	93.8	85.8	89.8
			MIN.	57.6	0.007	0	1.22	0.64	92.7	84.9	89.4
17 SOUTH CALIFORNIA	10	40	MAX.	60.9	0.070	2	2.17	1.27	94.3	86.6	90.1
			AVE.	59.2	0.031	1	1.17	0.40	93.3	85.4	89.4
			MIN.	57.3	0.015	0	0.86	0.37	91.4	83.4	87.4



TABLE A-4. REGULAR AUTOGAS DATA (REF. 12)  
WINTER, 1978-79 (Continued)

R.V.P. ASTM D 323 P.S.T.	20 V/L ASTM D 419 °F	DISTILLATION, ASTM D 86										RESIDUAL %	LOSS %
		TEMPERATURE, °F (CORRECTED TO 760 MM HG)											
		INITIAL BOILING PT.	PERCENT EVAPORATED								END POINT		
			5	10	20	30	50	70	90	95			
13.8 12.6 11.1	127 120 113	83	93	106	127	155	208	272	343	378	409	0.6	2.3
14.6 12.7 9.9	140 127 110	82	92	104	126	147	204	267	346	381	421	0.9	2.5
12.2 11.4 9.4	122 124 118	85	97	110	120	152	203	262	341	378	415	0.9	1.6
14.1 13.0 10.0	127 116 111	82	91	101	111	143	194	252	338	377	412	0.7	2.6
14.9 13.1 9.6	128 118 110	80	92	102	112	148	202	268	350	381	414	0.9	2.0
13.3 12.7 12.0	122 119 116	83	97	107	128	157	205	260	344	383	417	1.0	1.6
14.9 13.6 11.9	122 116 113	82	93	103	113	148	202	260	340	383	421	0.9	2.2
13.5 12.1 10.9	127 121 112	84	96	108	127	151	200	258	337	370	409	0.8	1.9
14.2 12.9 11.1	121 115 110	82	90	99	118	141	195	248	328	368	409	0.7	2.2
12.9 12.0 10.2	124 118 114	85	99	104	121	140	187	244	323	362	397	0.8	1.8
14.7 12.3 10.6	126 118 107	84	94	105	124	149	197	249	322	371	409	0.9	2.0
13.3 12.0 10.5	126 121 115	85	98	108	127	149	200	267	338	379	413	0.7	1.3
13.2 11.3 7.2	127 124 112	86	99	113	134	157	205	258	331	367	410	0.8	2.1
14.9 12.7 11.6	125 119 111	84	94	105	127	152	204	256	329	373	415	0.8	3.4
13.4 12.8 12.5	122 120 117	81	96	105	121	137	207	263	319	373	414	1.2	3.2
12.6 11.3 9.6	123 127 116	84	98	112	128	162	211	264	322	364	411	1.1	2.5
12.1 11.2 10.2	131 127 123	84	97	112	125	159	211	270	341	371	414	1.0	1.9

TABLE A-5. PREMIUM AUTOGAS DATA (REF. 12) WINTER, 1978-79

DISTRICT NO. AND NAME	NO. OF BRANDS	NO. OF SAMPLES		A. F. I. GRAVITY ASTM D 287	SULFUR ASTM D 1266 WT. %	GUM ASTM D 381 MG	SEVERINE ASTM D 3606 VOL. %	LEAD G/GAL	OCTANE NUMBER		
									RESEARCH ASTM D 2699	MOBILE ASTM D 2700	2+M 2
1 NORTHEAST	7	7	MAX.	64.5	—	—	—	3.05	91.2	91.7	95.2
			Avg.	63.0	—	—	—	2.65	90.3	90.5	94.4
			MIN.	61.2	—	—	—	2.17	97.2	89.3	93.9
2 MID-ATLANTIC COAST	15	79	MAX.	64.6	0.049	2	2.20	3.22	91.3	92.2	95.8
			Avg.	61.8	0.026	1	0.76	2.78	90.1	90.4	94.2
			MIN.	57.6	0.008	0	0.62	1.76	97.6	88.8	93.2
3 SOUTHEAST	14	34	MAX.	64.1	—	2	—	3.21	90.7	91.0	94.7
			Avg.	61.5	—	0	—	2.36	90.1	90.5	94.3
			MIN.	58.4	—	0	—	1.97	96.8	89.6	93.2
4 APPALACHIAN	11	32	MAX.	67.9	0.013	2	1.01	2.07	91.7	90.7	94.9
			Avg.	62.2	0.013	2	0.80	2.06	90.3	90.2	94.3
			MIN.	58.2	0.013	1	0.59	1.17	97.2	89.4	93.6
5 MICHIGAN	8	17	MAX.	67.0	0.042	2	1.20	3.03	90.7	91.2	94.7
			Avg.	63.0	0.030	1	0.79	2.03	97.1	90.2	94.1
			MIN.	60.5	0.016	1	0.58	1.02	97.0	89.4	93.6
6 NORTH ILLINOIS	7	9	MAX.	64.5	0.025	4	3.40	2.29	90.2	91.0	94.6
			Avg.	61.8	0.017	2	1.84	1.34	97.2	89.5	93.4
			MIN.	59.7	0.008	0	0.60	0.01	95.2	86.9	91.1
7 CENTRAL MISSISSIPPI	10	18	MAX.	67.3	0.022	2	1.05	2.46	90.5	91.2	94.6
			Avg.	63.3	0.020	1	0.78	1.93	90.0	90.3	94.2
			MIN.	60.4	0.018	1	0.45	0.01	97.6	89.0	93.2
8 LOWER MISSISSIPPI	8	17	MAX.	64.8	—	1	—	4.21	94.5	93.6	96.6
			Avg.	62.1	—	0	—	2.61	90.3	91.0	94.7
			MIN.	59.0	—	0	—	1.45	97.8	89.6	93.7
9 NORTH PLAINS	7	7	MAX.	66.4	—	—	—	2.09	92.4	91.2	94.7
			Avg.	64.0	—	—	—	1.86	90.0	90.4	94.2
			MIN.	59.4	—	—	—	1.60	97.0	88.8	93.4
10 CENTRAL PLAINS	6	9	MAX.	67.8	—	0	—	2.24	91.6	91.7	95.5
			Avg.	65.0	—	0	—	1.41	90.5	90.7	94.6
			MIN.	56.1	—	0	—	0.00	97.4	87.6	92.5
11 SOUTH PLAINS	17	34	MAX.	72.2	0.060	4	1.13	2.43	91.3	94.2	95.4
			Avg.	63.9	0.037	1	0.64	2.34	90.2	91.4	94.8
			MIN.	58.5	0.025	0	0.35	1.80	96.9	90.0	94.1
12 SOUTH TEXAS	10	19	MAX.	64.7	—	3	—	3.33	90.8	91.6	95.1
			Avg.	62.9	—	2	—	2.47	90.6	90.3	94.3
			MIN.	60.0	—	2	—	1.59	97.9	89.8	93.9
13 SOUTH MOUNTAIN STATES	17	71	MAX.	68.5	0.068	2	2.00	3.11	90.9	93.6	95.8
			Avg.	61.1	0.046	2	1.30	2.06	97.3	90.0	93.7
			MIN.	56.8	0.032	1	0.79	1.40	95.3	87.5	91.4
14 NORTH MOUNTAIN STATES	13	33	MAX.	70.1	0.051	2	—	1.82	90.8	91.1	94.9
			Avg.	66.2	0.037	1	—	1.40	97.6	90.0	93.8
			MIN.	62.3	0.025	1	—	0.64	96.6	88.2	92.4
15 PACIFIC NORTHWEST	8	19	MAX.	63.1	0.049	2	2.13	2.07	90.6	90.3	94.2
			Avg.	60.7	0.021	1	1.42	1.31	90.0	89.6	93.8
			MIN.	58.1	0.010	1	0.40	0.63	97.4	88.1	92.8
16 NORTH CALIFORNIA	10	29	MAX.	62.6	0.020	3	2.24	2.49	91.2	91.0	94.7
			Avg.	58.5	0.013	1	1.76	1.85	90.2	90.3	94.3
			MIN.	55.9	0.006	0	1.15	1.12	96.7	89.9	93.9
17 SOUTH CALIFORNIA	12	47	MAX.	62.2	0.046	1	1.33	2.48	90.6	90.6	94.4
			Avg.	59.3	0.020	1	1.16	1.81	97.9	90.0	93.8
			MIN.	54.9	0.007	0	0.84	1.03	97.0	89.8	93.7

TABLE A-5. PREMIUM AUTOGAS DATA (REF. 12)  
WINTER, 1978-79 (Continued)

K. V. F. ASTM D 223 P. S. T.	20 V/L ASTM D 431 °F	DISTILLATION, ASTM D 86											REGIONAL %	LOSS %
		TEMPERATURE, °F (CORRECTED TO 760 MM HG)										END POINT		
		INITIAL BOILING PT.	PERCENT EVAPORATED											
			5	10	20	30	50	70	90	99				
14.6 13.4 10.4	129 119 110	83	93	103	124	144	202	262	332	363	403	0.6	1.9	
14.3 12.4 9.3	124 121 112	82	94	103	125	144	210	267	338	370	411	0.9	2.5	
12.7 11.4 10.3	124 123 119	85	99	110	130	154	208	269	333	373	412	0.7	1.7	
10.3 12.2 12.0	121 116 107	81	90	100	119	143	204	261	333	370	414	0.8	3.1	
14.3 12.7 10.1	121 120 114	81	93	103	126	152	209	261	338	375	419	0.8	2.1	
12.4 10.2 10.4	124 123 118	84	97	109	122	159	213	291	333	376	414	1.0	1.8	
11.8 11.0 11.4	124 118 112	81	92	103	125	152	205	290	326	370	408	0.8	2.5	
12.4 12.2 11.3	123 121 116	84	97	107	127	151	206	260	333	364	402	0.8	1.7	
11.8 11.2 9.0	123 116 114	84	97	108	132	161	209	241	323	364	404	0.6	2.0	
11.0 12.3 10.1	125 121 117	84	92	105	127	156	208	249	320	369	409	0.8	2.1	
10.2 12.0 9.3	120 123 116	83	95	108	132	159	208	264	327	364	406	0.9	2.2	
11.5 12.1 10.6	127 122 117	84	97	106	126	150	207	260	335	371	407	0.7	1.8	
11.4 11.3 10.0	122 127 119	86	100	113	134	165	214	259	332	368	412	0.9	2.1	
10.4 12.3 9.5	124 121 115	84	97	108	133	161	207	241	321	361	408	0.8	3.8	
11.2 12.2 10.3	120 122 115	81	92	105	130	158	211	288	320	355	401	1.2	3.0	
12.6 11.6 9.6	126 126 120	84	98	111	134	165	216	267	331	361	408	1.1	2.6	
12.2 11.2 10.1	124 127 122	84	94	104	130	163	211	261	333	361	409	1.0	1.7	

TABLE A-6. UNLEADED AUTOGAS DATA (REF. 12) WINTER, 1978-79

DISTRICT NO. AND NAME	NO. OF STATIONS	NO. OF SAMPLES		A. S. I. GRAVITY ASTM D 1557	SULFUR ASTM D 1266 WT. %	CUM ASTM D 1291 NO.	BROMINE ASTM D 1266 VOL. %	OCTANE NUMBER			A. V. P. ASTM D 153 F. S. I.
								RESEARCH ASTM D 1541	MO TNA ASTM D 1700	QAM Z	
1 NORTHEAST	14	28	MAX.	63.7	0.030	3	1.00	95.1	99.1	91.4	14.3
			Ave.	60.4	0.033	2	0.87	93.8	94.4	89.1	12.8
			MIN.	53.8	0.010	0	0.60	91.5	91.7	87.2	11.6
2 MID-ATLANTIC COAST	21	109	MAX.	63.1	0.044	2	1.05	98.8	97.4	91.0	14.5
			Ave.	60.1	0.035	1	1.00	91.4	94.2	88.8	13.0
			MIN.	56.4	0.009	0	0.45	91.5	91.7	87.3	10.4
3 SOUTHEAST	20	94	MAX.	62.5	0.030	3	1.70	91.4	88.1	91.5	12.4
			Ave.	59.4	0.032	1	1.27	93.1	94.2	89.7	11.4
			MIN.	51.0	0.010	0	0.70	91.5	91.9	87.5	9.5
4 APPALACHIAN	18	55	MAX.	64.4	0.028	2	3.91	97.9	97.1	92.3	14.4
			Ave.	61.3	0.018	2	1.97	93.3	94.3	89.8	12.0
			MIN.	56.8	0.002	1	0.77	91.3	93.1	87.4	9.2
5 MICHIGAN	13	47	MAX.	67.8	0.062	2	2.80	97.3	97.4	91.4	15.6
			Ave.	62.1	0.023	1	0.99	93.0	94.9	89.0	13.6
			MIN.	57.6	0.005	0	0.33	91.2	93.5	87.5	11.6
6 NORTH KENTUCKY	12	28	MAX.	65.3	0.105	2	3.10	98.2	97.5	91.4	15.8
			Ave.	61.2	0.044	1	1.60	94.8	94.1	88.5	12.6
			MIN.	56.9	0.008	0	1.00	91.0	91.3	87.0	10.8
7 CENTRAL MISSISSIPPI	23	49	MAX.	67.2	0.031	1	1.13	97.5	97.8	91.5	14.2
			Ave.	62.8	0.023	1	0.78	92.9	94.2	89.6	13.2
			MIN.	58.7	0.010	0	0.80	90.8	91.6	87.3	11.0
8 LOWER MISSISSIPPI	18	49	MAX.	64.2	0.040	2	0.60	94.0	91.2	93.4	13.2
			Ave.	59.9	0.040	1	0.60	93.6	94.7	89.2	12.2
			MIN.	55.7	0.040	0	0.60	91.5	93.2	87.6	10.0
9 NORTH PLAINS	13	13	MAX.	68.0	—	—	—	98.0	97.4	91.7	14.2
			Ave.	63.8	—	—	—	92.8	94.4	89.6	12.7
			MIN.	58.3	—	—	—	91.8	91.9	87.4	10.7
10 CENTRAL PLAINS	12	46	MAX.	64.0	—	1	—	98.0	97.0	91.5	13.2
			Ave.	62.0	—	1	—	93.0	94.2	89.6	12.0
			MIN.	55.5	—	0	—	91.8	93.2	87.7	9.4
11 SOUTH PLAINS	26	73	MAX.	67.9	0.060	4	1.05	96.7	96.8	91.8	13.5
			Ave.	61.9	0.030	2	1.01	92.4	94.4	89.4	12.4
			MIN.	56.6	0.011	0	0.36	91.2	91.6	87.0	10.1
12 SOUTH TEXAS	14	42	MAX.	63.6	—	3	—	96.8	97.0	91.4	13.5
			Ave.	59.4	—	1	—	91.7	94.8	88.4	12.1
			MIN.	54.4	—	0	—	91.3	91.7	87.1	11.3
13 SOUTH MOUNTAIN STATES	21	117	MAX.	65.5	0.031	3	2.14	96.4	96.4	91.4	12.5
			Ave.	61.0	0.023	1	1.16	91.8	93.4	87.6	11.5
			MIN.	58.2	0.008	0	1.00	89.3	90.4	85.0	10.2
14 NORTH MOUNTAIN STATES	17	47	MAX.	64.9	0.048	2	—	92.3	94.1	89.1	14.2
			Ave.	62.8	0.035	1	—	91.6	93.2	87.4	12.5
			MIN.	61.1	0.017	1	—	91.0	93.3	86.4	11.2
15 PACIFIC NORTHWEST	10	27	MAX.	63.2	0.063	2	2.31	97.8	96.0	93.4	13.5
			Ave.	59.8	0.047	1	1.54	93.8	96.3	94.5	13.8
			MIN.	56.8	0.004	1	1.12	91.6	91.5	88.1	12.1
16 NORTH CALIFORNIA	12	48	MAX.	62.7	0.024	1	2.62	96.1	96.1	91.1	12.8
			Ave.	57.8	0.013	1	1.78	94.0	94.5	89.2	11.2
			MIN.	51.6	0.003	0	1.15	91.7	93.0	87.5	10.7
17 SOUTH CALIFORNIA	15	47	MAX.	59.9	0.026	4	2.51	96.5	96.0	91.1	12.1
			Ave.	56.0	0.021	2	1.21	94.5	94.4	89.7	11.0
			MIN.	51.3	0.007	0	0.70	91.4	91.6	88.0	8.5

NOTED: 10-11-79  
ALL DATA SUBMITTED TO BUREAU

TABLE A-7. 80/87 AVGAS DATA (REFERENCE 13) FROM 1969

Inspection Data for Grade 80/87 Aviation Gasolines

Item	Octane number	Aviation, Motor, ASTM D2700	Aviation, Supercharge, ASTM D2700	Distillation, ASTM Method D86														Slope of distillation curve at 10 percent	Boil-over pressure, lb.	ASTM D323, lb.	Potential gum, 3 hr., ASTM D323, mg./100 ml.	Visible lead precipitate, ASTM D323, mg./100 ml.	Water tolerance, ASTM D1094, ml. 1/	Heat of combustion, Btu per lb., ASTM D1405	ASTM D415, °F.	Gravity, ASTM D287, °A <sup>2</sup>	Relative gravity, constant	Freezing point, °F., ASTM D2386	Sulfur (uncorrected for TCU), ASTM D1266, weight percent	Kinematic viscosity, ASTM D445, at 70° F., centistokes
				Temperature (corrected to sea level) °F.																										
				Percent evaporated																										
				10°	3°	10°	15°	20°	30°	40°	50°	60°	70°	80°	90°	95°	100°													
Commercial aviation gasoline																														
1	84.12/	88.3	0.00	111	136	145	154	163	176	184	196	213	233	254	303	341	0.9	6.6	0.4	0.0	0.0	0.0	0.0	19,015	155	73.0	11,315	<50	0.01	0.37
2	86.02/	90.0	0.00	119	140	147	154	163	176	180	190	211	229	243	273	332	1.1	6.1	1.3	0.0	0.0	0.0	0.0	19,015	149.4	73.0	11,315	<50	0.01	0.37
3	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,007	155.3	73.0	11,315	<50	0.01	0.37
4	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
5	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
6	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
7	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
8	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
9	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
10	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
11	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
12	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
13	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
14	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
15	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
16	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
17	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
18	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
19	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
20	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
21	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
22	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
23	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
24	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
25	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
26	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
27	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
28	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
29	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
30	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
31	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
32	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
33	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
34	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
35	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
36	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
37	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
38	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
39	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
40	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
41	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
42	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
43	88.1	91.7	0.00	127	150	164	173	182	192	200	208	216	234	255	310	353	1.0	6.1	1.3	0.0	0.0	0.0	0.0	19,014	154.5	73.0	11,315	<50	0.01	0.37
44	88.1	91.7	0.00	127	150	164	173	182	192	200																				

APPENDIX B

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